MIDDLE EAST TECHNICAL UNIVERSITY

Electrical and Electronics Engineering Department

EE568 Selected Topics on Electrical Machines

PROJECT 4

DESIGN AN INDUCTIVE POWER TRANSFER INDUCTANCE AND ANALYSIS of MISALIGNMENT

Enes AYAZ 2093318

Contents

Introduction

Inductive power transfer (IPT) has become more popular in recent years. It is used in range area from low power applications to high power applications. [1-2] Cordless design and spatial flexibility of IPTs led them to be used in some applications such as portable chargers, biomedical implements, etc. [3] Also, providing electrical safety and galvanic isolation make them the future of the electric car chargers and energy harvesting systems, etc. [4]

In many applications (Electric vehicle, portable chargers), IPT system is used for multiple loads. [5] For these applications, the position of transmitter and receivers are variable. Thus, the loosely coupled IPT's have a variable mutual inductance between transmitter and receiver. The different mutual inductance affects the output power, output voltage and the efficiency of the system. [6] In general, the small changes on mutual inductance can be tolerated by using frequency or phase shift control. However, small position changes on loosely coupled systems led the mutual inductance change drastically. Thus, transmitter and receiver coils should be designed to be misalignment tolerant. In literature, misalignment tolerant IPT systems are well investigated and the misalignments can be also changed with respect to coil shape and there are different misalignment conditions such as vertical, planar and angular etc. [7-9]. The misalignment tolerant system come into view in two points. One of them is that the misalignment tolerant system is done with control methods [10] and the method is out of topic for our work. Other one is that the misalignment tolerant system is done with designing misaligned tolerant coils. In literature, the misaligned tolerant coils are investigated in different solutions. For example, it is proposed a two-plane printed transmitter to avoid separation-misalignment in the paper. [11] In addition, the analytical calculation of mutual inductance for square coils are investigated by considering misalignment in another work. [12] Also, an analytic solution for wireless power transfer in electric vehicle is analyzed in this paper. [13]. Finally, the angular misalignment analysis for circular coils are examined [14] and our topology and calculations are strongly related this paper.

In this report, a contactless slip ring with series-series inductive power transfer will be investigated. The system design and required inductance value is taken in the paper. We will design a transmitter and receiver inductance and we will analyze the misalignment condition of the coupled inductances. Firstly, a coupled coil is designed and the mutual inductance between coils are calculated analytically. Secondly, the design is simulated by FEA. Finally, the analytical and FEA model are compared and the design will be optimized.

Analytical Calculation and Sizing

In this part, we chose inductor shape which are suitable to our applications. Our application is a contactless slip rings and it requires a planar misalignment tolerant in shown figure 1. Thus, circular shape coil is chosen to provide planar symmetry. The value of self-inductances and mutual inductance were calculated with respect to the paper [15]. The values are shown at table 1. However, the values can be slightly different. It will be adjusted at system design.

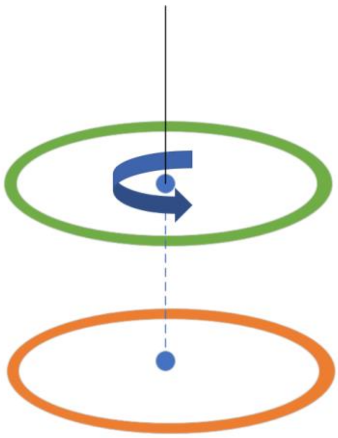

Figure 1 Planar Symmetric Coils

Table 1 Magnetic Parameters of IPT system

Inductances	**Values**
Transmitter Inductance	81μH
Receiver Inductance	68μH
Mutual Inductance	14μH

In this section, we will calculate the self-inductances and mutual inductance between transmitter and receiver coil analytically by using vector potential approach.

Self-Inductance Calculations

The inductance of a loop of wires shown at figure 2 can be calculated by using the formula.

$$L = N^2 R\, \mu_r \mu_0 [\ln\left(\frac{8R}{a}\right) - 2]$$

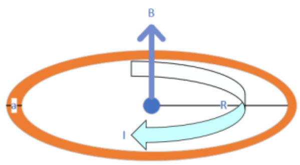

Figure 2 A circular coil

By using the formula, we can calculate the transmitter and receiver inductances. In this part, we want to design a coil with angular misalignment tolerant. Thus, the radius of receiver is chosen smaller than transmitter which will be explained later. We can simplify it for single coil and find average radius single coil inductance between 0.06 m and 0.14 m as below:

$$L_{single} = R_{average}\, \mu_r \mu_0 [\ln\left(\frac{8R_{average}}{a}\right) - 2]$$

$$L_{single} = \mu_r\, (1.31e^{-6} R_{average} + 4.52e^{-7})$$

Then we can multiply to single coil inductance with square of turn ratio.

$$L = N^2 \mu_r\, (1.31e^{-6} R_{average} + 4.52e^{-7})$$

Also, we can linearize the inductance while radius is between 0.04 and 0.08.

$$L = N^2 \mu_r\, (2.16e^{-6} R_{average} + 3.91e^{-7})$$

Mutual Inductance Calculations

Mutual inductance between two circular coils as shown figure 3. are calculated by using vector potential approach. [14] The mutual inductance formula as known Neumann's formula is shown below.

$$M = \frac{N_1 N_2 \mu_0}{4\pi} \oint \oint \frac{dl_1 x dl_2}{R}$$

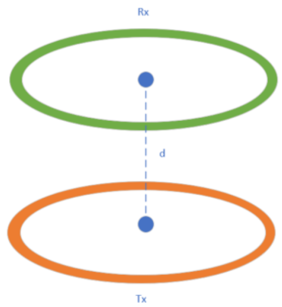

Figure 3 Aligned circular coupled coils

Where the dl_1 and dl_2 are defined as:

$$dl_1 = \left(-r_1 \sin(\theta_i) + r_1 \cos(\theta_j)\right) d\theta$$

$$dl_2 = \left(-r_1 \sin(\phi_i) + r_1 \cos(\phi_j)\right) d\phi$$

Then, two arbitrary points of coils, we define R as:

$$R = \sqrt{r_1^2 + r_2^2 - 2r_1 r_2 \cos(\theta - \phi) + d^2}$$

By using the definitions, we can calculate the mutual inductances as:

$$M = \frac{N_1 N_2 \mu_0}{4\pi} \oint_0^{2\pi} \oint_0^{2\pi} \frac{r_1 r_2 \cos(\theta - \phi)\, d\theta d\phi}{\sqrt{r_1^2 + r_2^2 - 2 r_1 r_2 \cos(\theta - \phi) + d^2}}$$

For misaligned coils shown at figure 4 and 5, we can change the coordinate systems. Lateral and angular misalignment can be represented as translation and rotation of coordinate system. Thus, we can show that the position of receiver coil as:

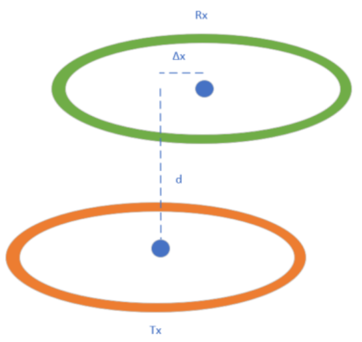

Figure 4 Lateral misaligned coils

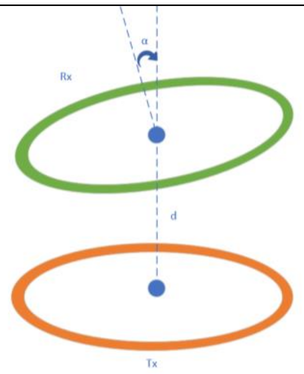

Figure 5 Angular misaligned coils

$$(x, y, z) = (r_2 cos\phi, r2 sin\phi cos\alpha + \Delta y, r_2 sin\phi \sin\alpha + d\ )$$

or

$$(x, y, z) = (r_2 cos\phi cos\alpha + \Delta x, r2 sin\phi, r_2 sin\phi \sin\alpha + d\ )$$

Then, we can calculate the mutual inductance by considering the misalignment.

$$M\ = \frac{N_1 N_2 \mu_0}{4\pi} \oint_0^{2\pi} \oint_0^{2\pi} \frac{r_1 r_2 (sin\theta sin\phi + cos\alpha cos\theta cos\phi) d\theta d\phi}{\sqrt{(r_1 cos\theta - r_2 cos\phi)^2 + (r_1 sin\theta - r_2 sin\phi cosa - \Delta y)^2 + (r_2 sin\phi sin\alpha - d)^2}}$$

Parameter Determination

Firstly, the parameters are calculated for aligned condition and receiver part with two different average radii. Then, the parameters are optimized to provide angular misalignment tolerant coils. However, the optimization will be made at section 4 after FEA analysis is done.

Inductances	**Formula**	**N**	$\boldsymbol{R_{average}}$ $\boldsymbol{/d_{mutual}}$	**Values**
Transmitter Inductance	$L = N^2\mu_r\,(1.31e^{-6}R_{average} + 4.52e^{-7})$	12	0.1 m	$84.77\mu H$
Receiver Inductance	$L = N^2\mu_r\,(2.16e^{-6}R_{average} + 3.91e^{-7})$	11	0.075 m	$66.8\mu H$
Receiver Inductance	$L = N^2\mu_r\,(1.31e^{-6}R_{average} + 4.52e^{-7})$	10.5	0.1 m	$64.9\ \mu H$
Mutual Inductance	$M = \frac{N_1N_2\mu_0}{4\pi}\oint_0^{2\pi}\oint_0^{2\pi}\frac{r_1\,r_2\cos(\theta-\phi)\,d\theta d\phi}{\sqrt{r_1^2+r_2^2-2r_1r_2\cos(\theta-\phi)+d^2}}$	-	0.03m	$13.95\ \mu H$
Mutual Inductance	$M = \frac{N_1N_2\mu_0}{4\pi}\oint_0^{2\pi}\oint_0^{2\pi}\frac{r_1\,r_2\cos(\theta-\phi)\,d\theta d\phi}{\sqrt{r_1^2+r_2^2-2r_1r_2\cos(\theta-\phi)+d^2}}$	-	0.05 m	$14.01\mu H$

FEA MODELLING

In this part circular planar coils are modelled by FEA. The model is established in 3D magnetostatics solution. The model is adjusted to obtain different size receiver with different misalignment conditions. We will analyses two misalignment conditions for each receiver. Firstly, we investigate the angular misalignment with same size coil. Secondly, we investigate the lateral misalignment with same size coil. After that, two misalignment conditions are investigated for smaller receiver coil.

Self-Inductance and Mutual Inductance

By using analytical solution, we establish the FEA analysis setup. However, some differences between analytical and FEA analysis due to assumptions (such as average radius). The differences are observed and the turn ratio of the transmitter and receiver part is updated until the values are reached. Then, the mutual inductance is optimized by changing distance of center point of two coils.

The table 2 show that the new parameters of the inductances at aligned position.

Table 2 Design parameters of coupled coils

	Same Size Coils	Smaller Receiver Coils
N_p	15	15
N_s	13	16
d	70mm	60mm
r_{in}^{tx}	88mm	88mm
r_{in}^{rx}	89.5mm	60mm
L_{tx}	81.147 µH	81.185 µH
L_{rx}	63.634 µH	65.2 µH
M	16.45 µH	16.985 µH

a. Same size with angular misalignment

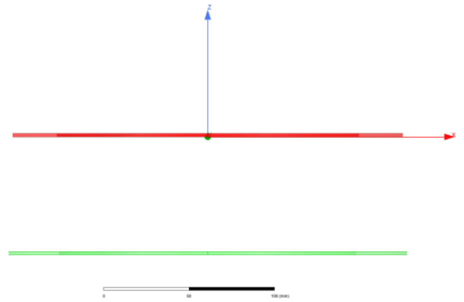

Figure 6 Aligned coils with same size

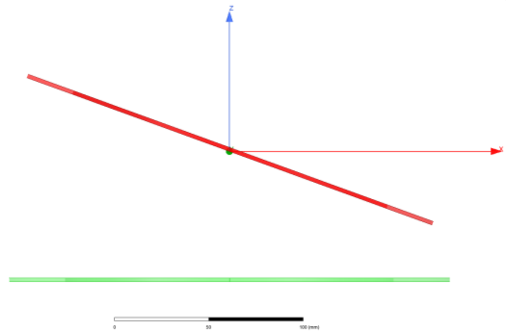

Figure 7 Angular misaligned coils with same size

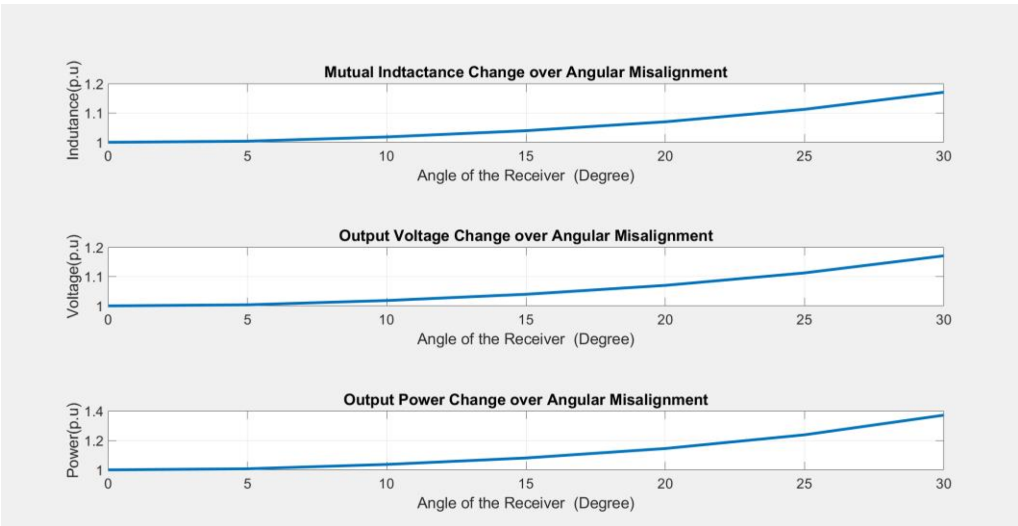

Figure 8 Change on mutual inductance, output power and voltage over angular misalignment

Figure 6 and 7 shows the changing condition and we observe that angular misalignment led the mutual inductance increases as shown figure 8. Although it looks good at first, the more mutual inductance can cause bifurcation. Also, we observe that change on output voltage is proportional to change on mutual inductance and change on output power is proportional to the square of change on mutual inductance.

b. Same size with lateral misalignment

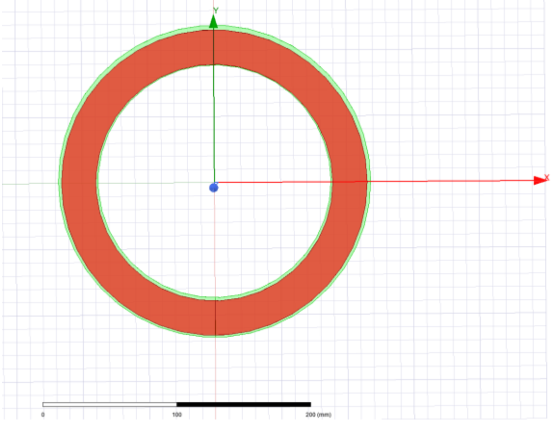

Figure 9 Aligned coils with same size

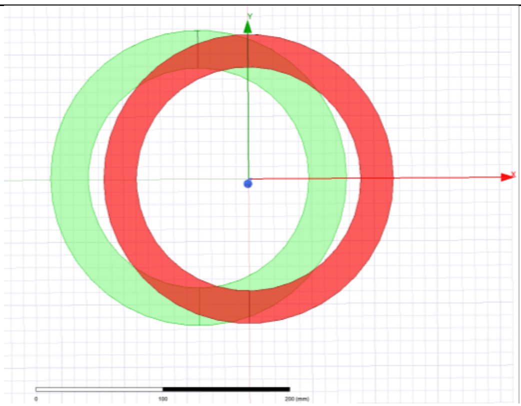

Figure 10 Lateral misaligned coils with same size

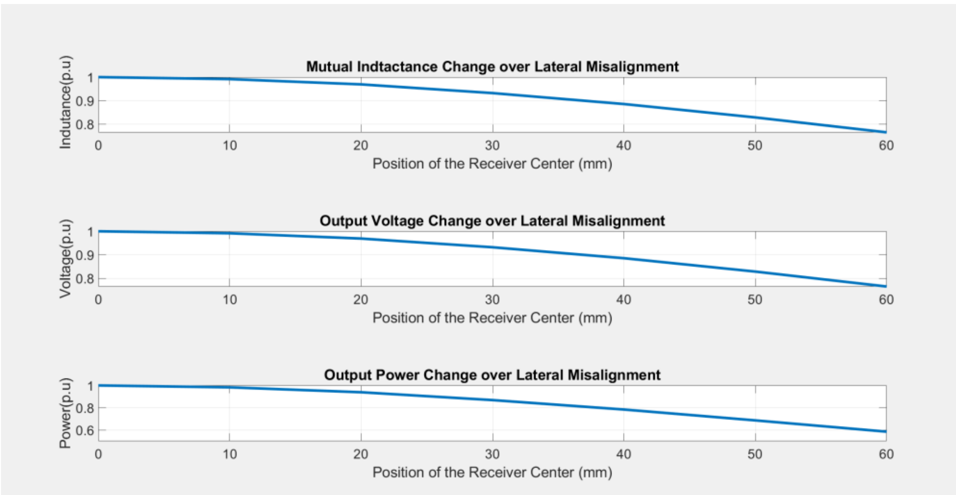

Figure 11 Change on mutual inductance, output power and voltage over angular misalignment

Figure 9 and 10 shows the changing conditions and we observe that the mutual inductance decreases while position of the center of the receiver is sliding as shown figure 11.

c. Smaller receiver with angular misalignment

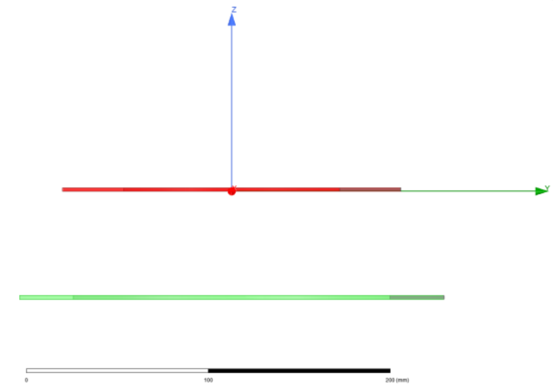

Figure 12 Aligned coils with smaller receiver

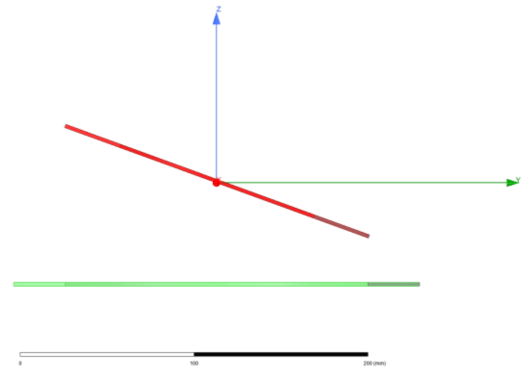

Figure 13 Angular misaligned coils with smaller receiver

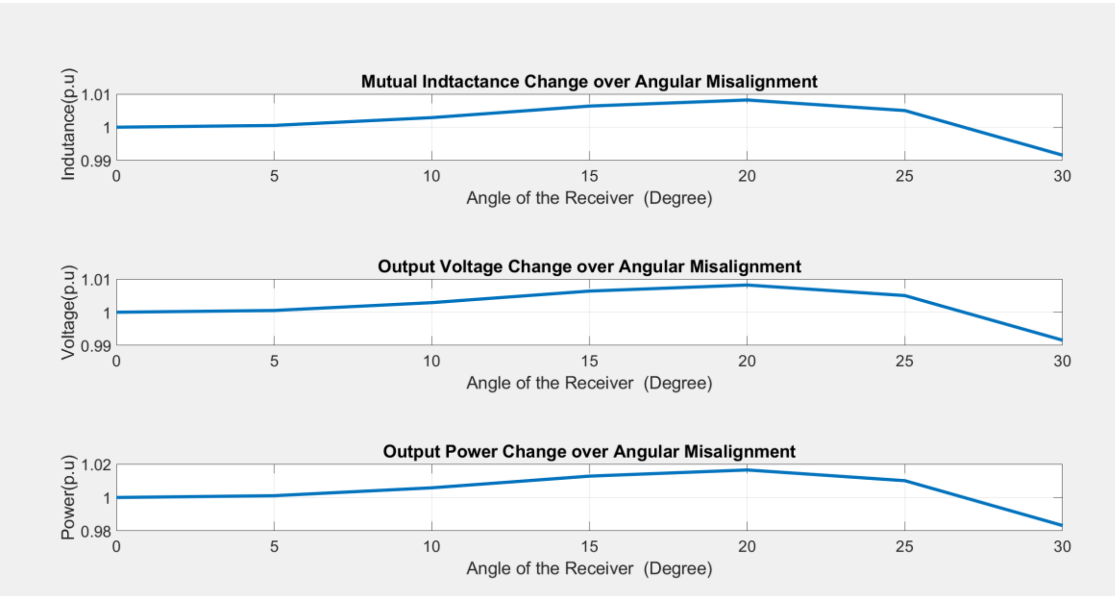

Figure 14 Change on mutual inductance, output power and voltage over angular misalignment

Figure 12 and 13 shows the changing conditions and we observe that the mutual inductance is almost constant over the deviation of the receiver coil as shown figure 14. The change on output voltage and power is acceptable.

d. Smaller receiver with lateral misalignment

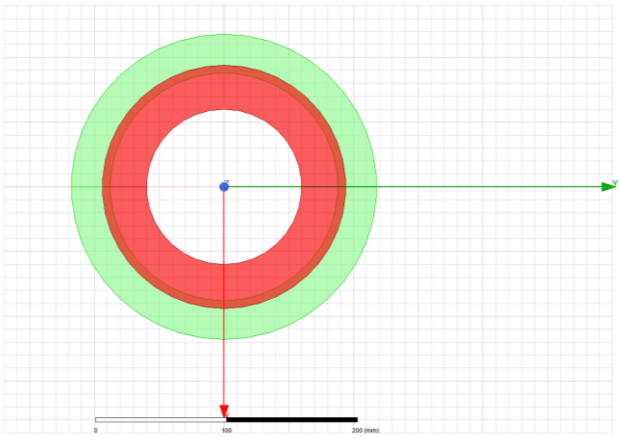

Figure 15 Aligned coils with smaller receiver

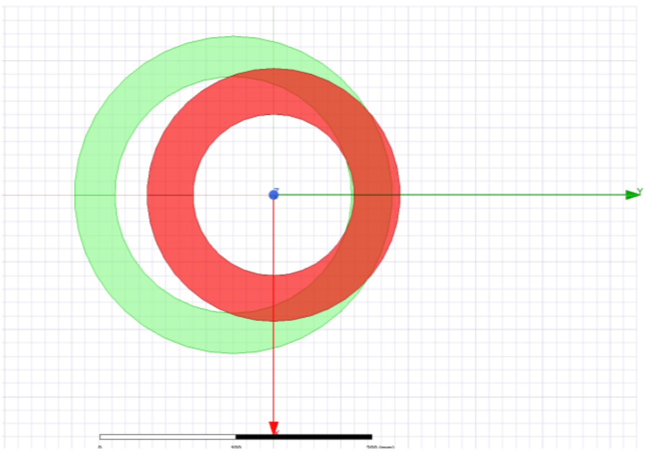

Figure 16 Lateral misaligned coils with smaller receiver

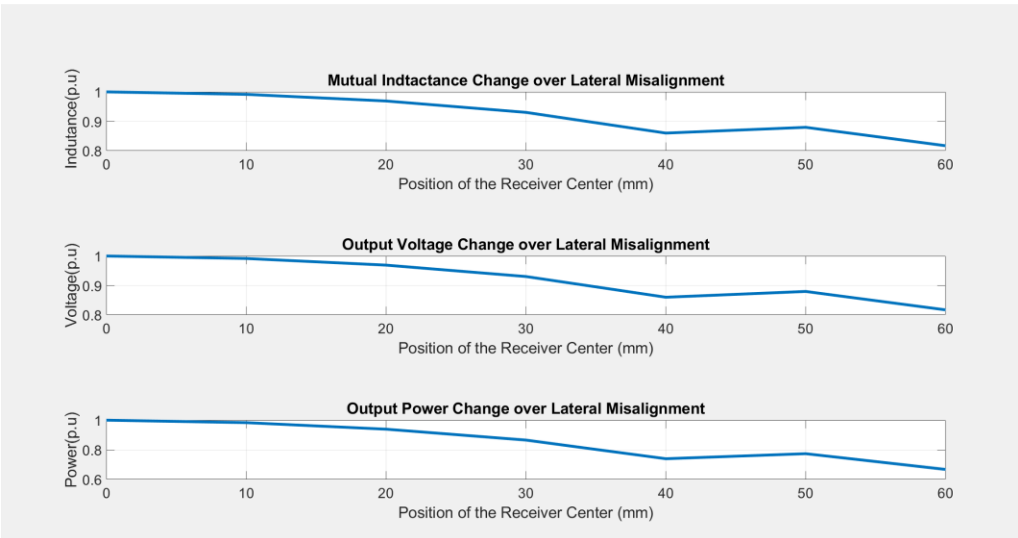

Figure 17 Change on mutual inductance, output power and voltage over angular misalignment

Figure 15 and 16 shows the changing conditions and we observe that the change on mutual inductance is smaller than counterpart of same size.

Comparison and Discussion

Misalignment tolerant design required to keep mutual inductance almost constant. We analysed lateral and angular misalignment problems due to our system has a planar symmetry. As seen figure 18, the angular misaligned is acceptable if the receiver part has smaller size. Although the same size gives %17 change at 30-degree misalignment, smaller receiver gives %1 change. Then, we should design the coils with smaller receiver.

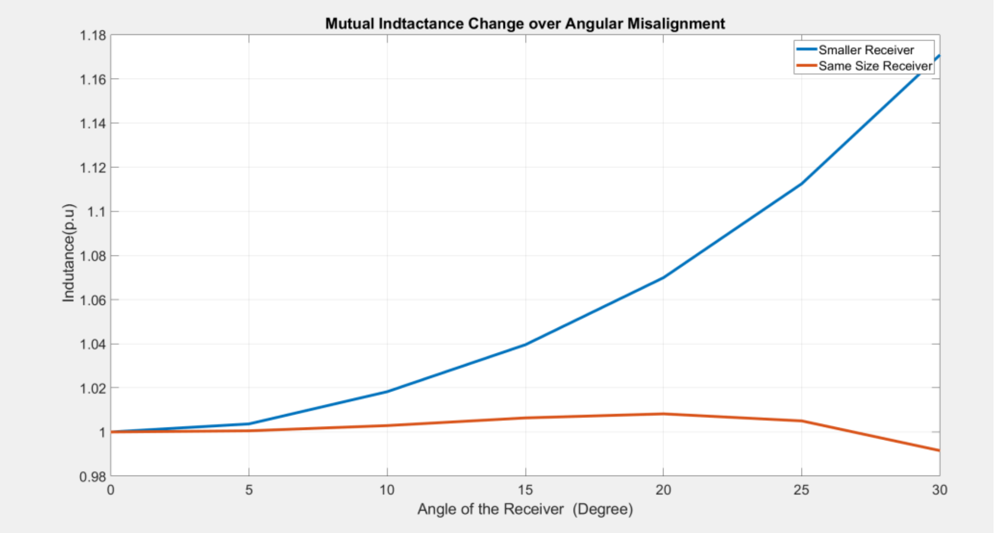

Figure 18 Change on mutual induction over angular misalignment

However, the lateral misalignment is a problem for smaller receiver. Figure 19 shows the change on mutual inductance with respect to position. We observed that, each coil design is not a tolerant to lateral misalignment but the change is acceptable until 30mm center shift. It brings the %8 change on mutual inductance.

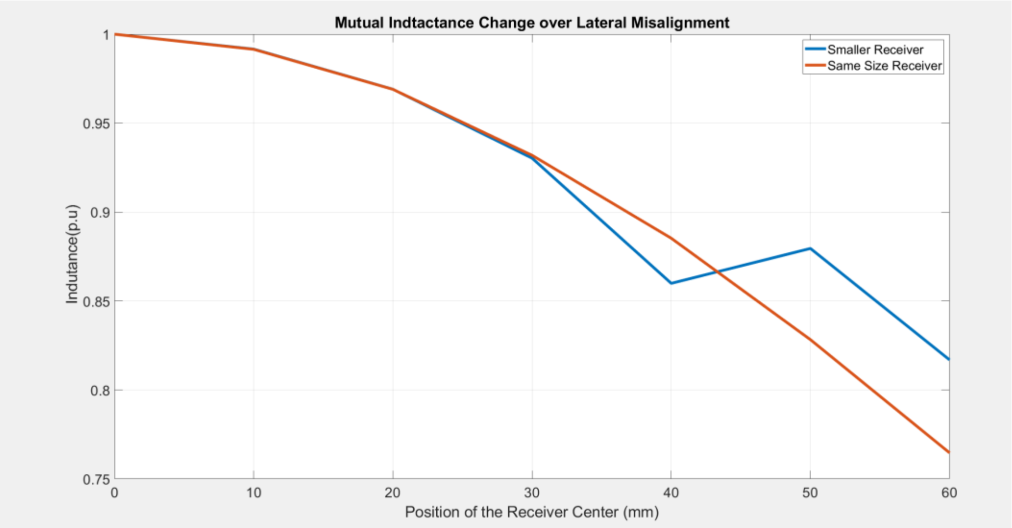

Figure 19 Change on mutual induction over lateral misalignment

Conclusion

In this report, a coupled coils design for inductive power transfer (IPT) was examined and misalignment analysis was done. Firstly, the requirement of misalignment tolerant IPT and proposed solutions in literature are reviewed. Secondly, we chose a suitable shape of coils for contactless slip ring applications and we calculate the inudctances analytically. Also, we used vector potential and we added the effect of lateral and angular misalignment.Thirdly, the design is modelled by using FEA. The turn ratios and distance between coils are taken from analytic solution.However, the results are different and we adjust the parameters at FEA. Both FEA and analytical solution show that the system can be angular misalignment tolerant by making smaller receiver. Finally, the smaller receiver and same-size receiver are compared with respect to output power, output voltages which are proportioanal to mutual inductance.

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