

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

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# 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.

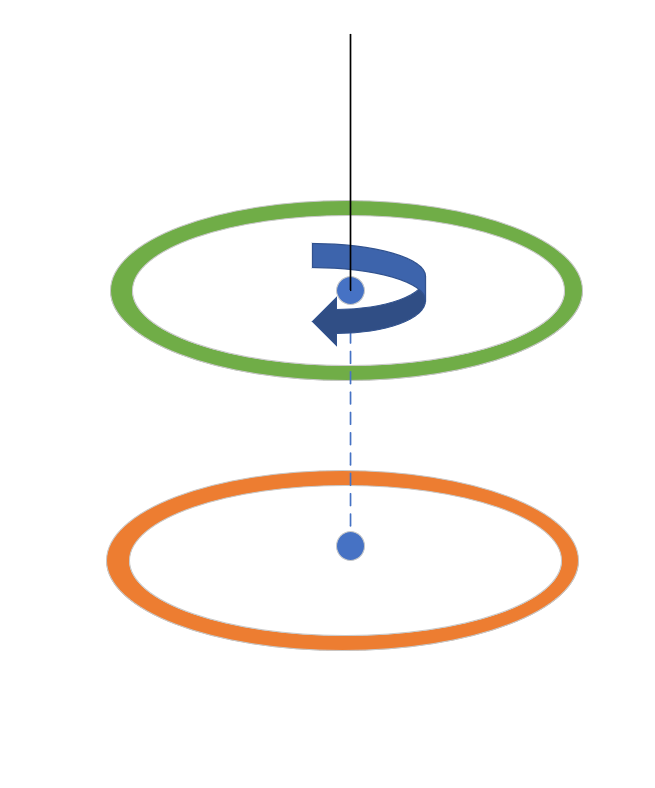


Figure Planar Symmetric Coils

Table Magnetic Parameters of IPT system

|  |  |
| --- | --- |
| **Inductances** | **Values** |
| Transmitter Inductance |  |
| Receiver Inductance |  |
| Mutual Inductance |  |

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.

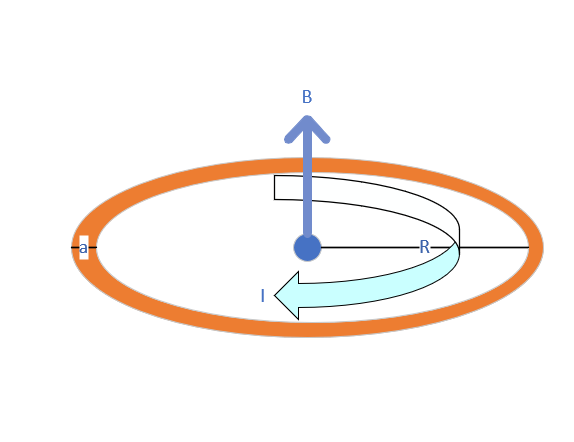


Figure A circular coil

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:

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

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

## 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.

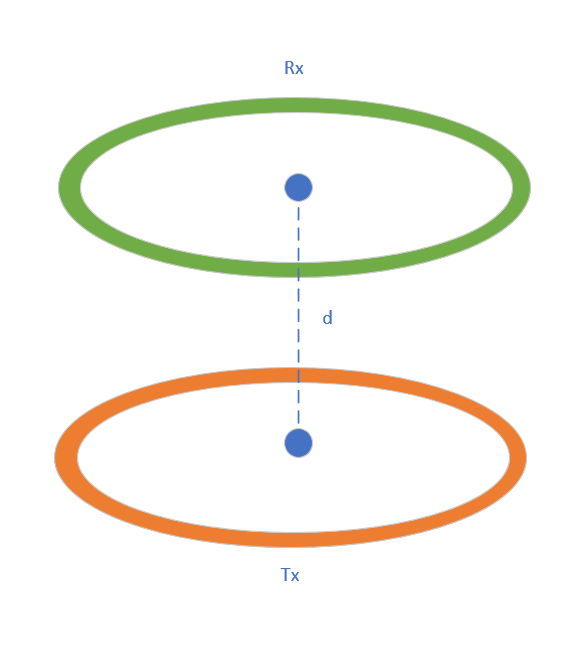


Figure Aligned circular coupled coils

Where the are defined as:

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

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

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 Lateral misaligned coils | Figure Angular misaligned coils |

or

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

## 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** |  | **Values** |
| Transmitter Inductance |  | 12 | 0.1 m | 84.77 |
| Receiver Inductance |  | 11 | 0.075 m | 66.8 |
| Receiver Inductance |  | 10.5 | 0.1 m | 64.9 |
| Mutual Inductance |  | - | 0.03m | 13.95 |
| Mutual Inductance |  | - | 0.05 m |  |

# 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 Design parameters of coupled coils

|  |  |  |
| --- | --- | --- |
|  | Same Size Coils | Smaller Receiver Coils |
|  | 15 | 15 |
|  | 13 | 16 |
|  | 70mm | 60mm |
|  | 88mm | 88mm |
|  | 89.5mm | 60mm |
|  |  |  |
|  |  |  |
|  |  |  |

### Same size with angular misalignment

|  |
| --- |
| Figure Aligned coils with same size |
| Figure Angular misaligned coils with same size |

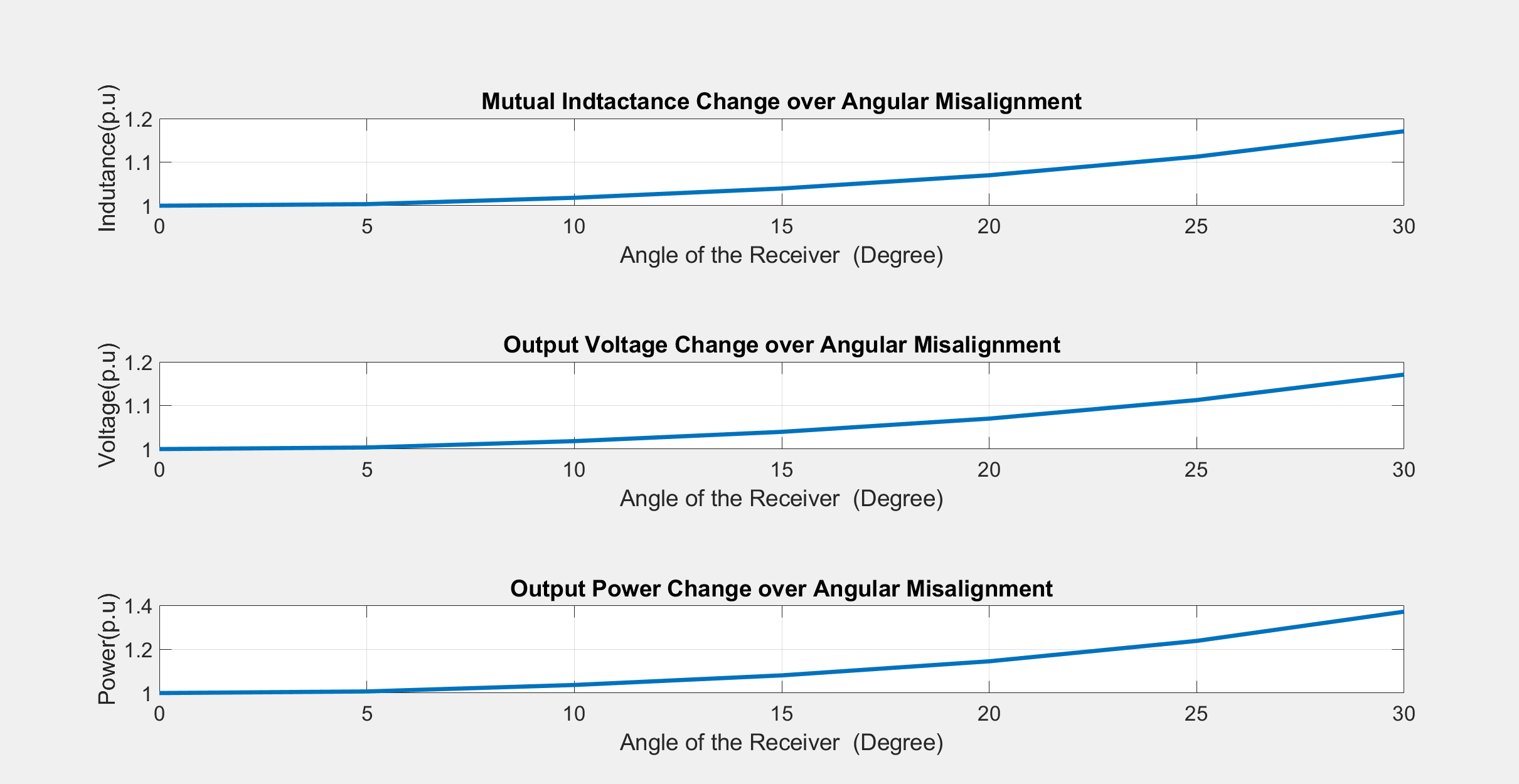


Figure Change on mutual inductance, output power and voltage over angular misalignment

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.

### Same size with lateral misalignment

|  |
| --- |
| Figure Aligned coils with same size |
| Figure Lateral misaligned coils with same size |

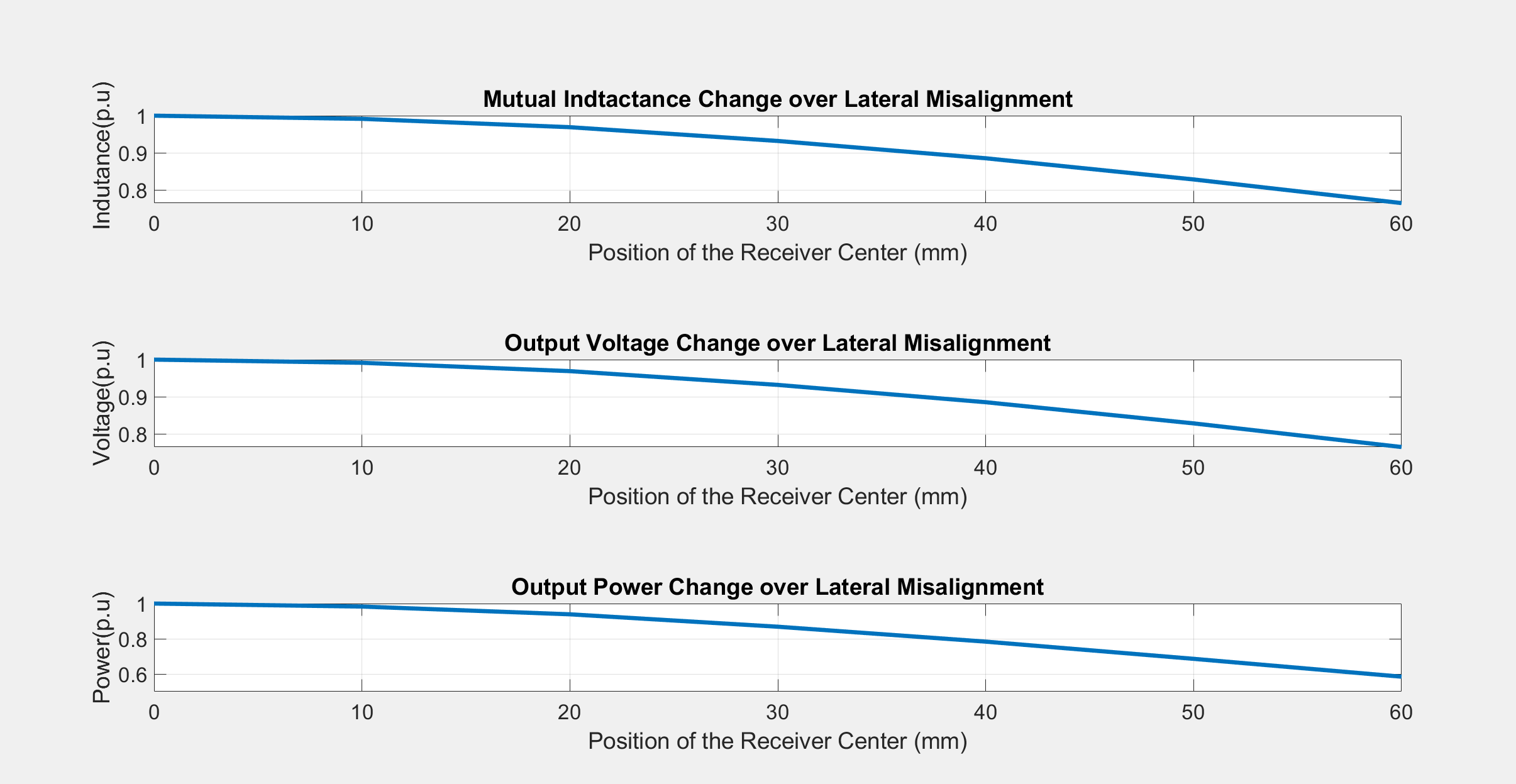


Figure Change on mutual inductance, output power and voltage over angular misalignment

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.

### Smaller receiver with angular misalignment

|  |
| --- |
| Figure Aligned coils with smaller receiver |
| Figure Angular misaligned coils with smaller receiver |

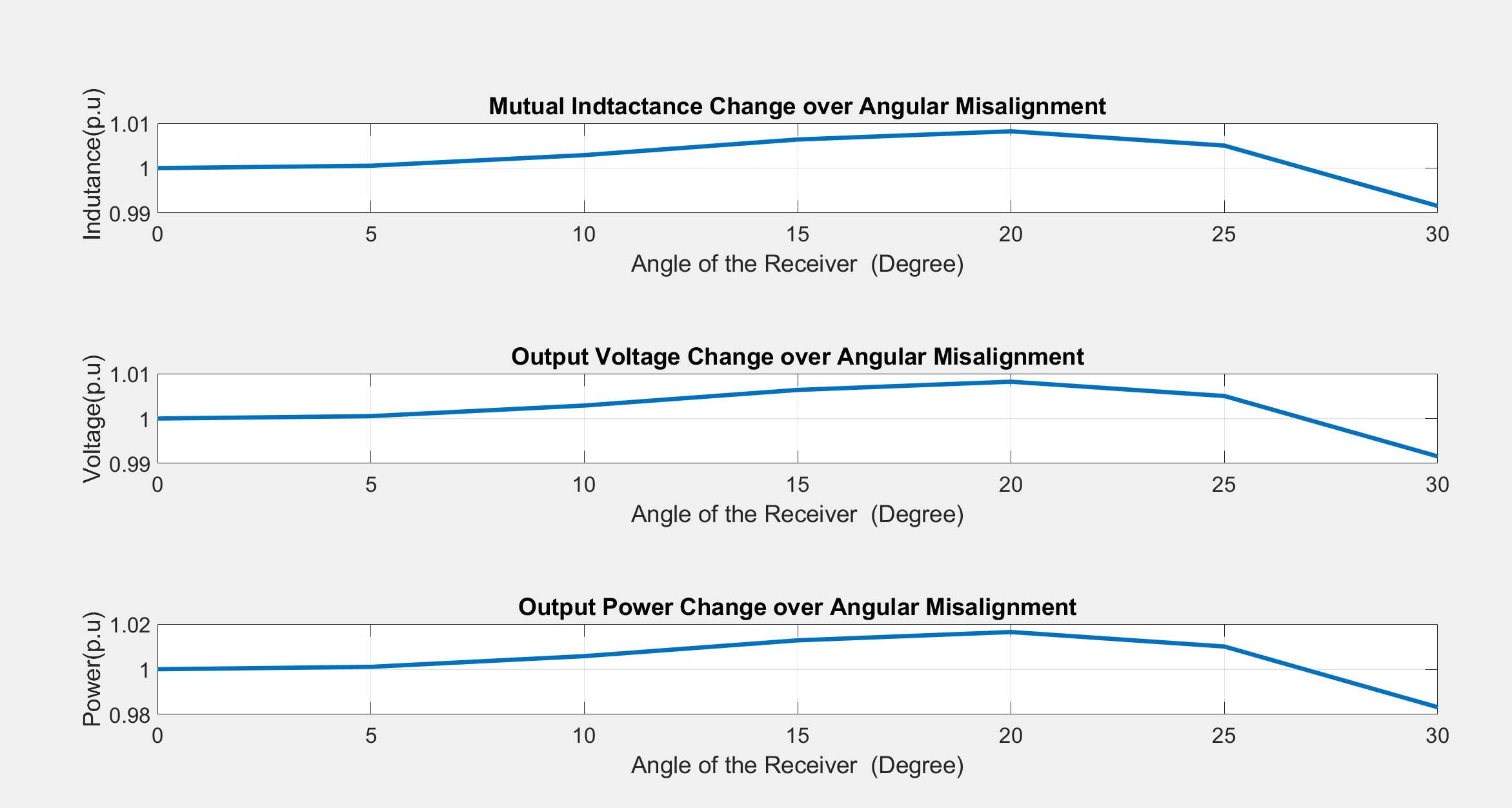


Figure Change on mutual inductance, output power and voltage over angular misalignment

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.

### Smaller receiver with lateral misalignment

|  |
| --- |
| Figure Aligned coils with smaller receiver |
| Figure Lateral misaligned coils with smaller receiver |

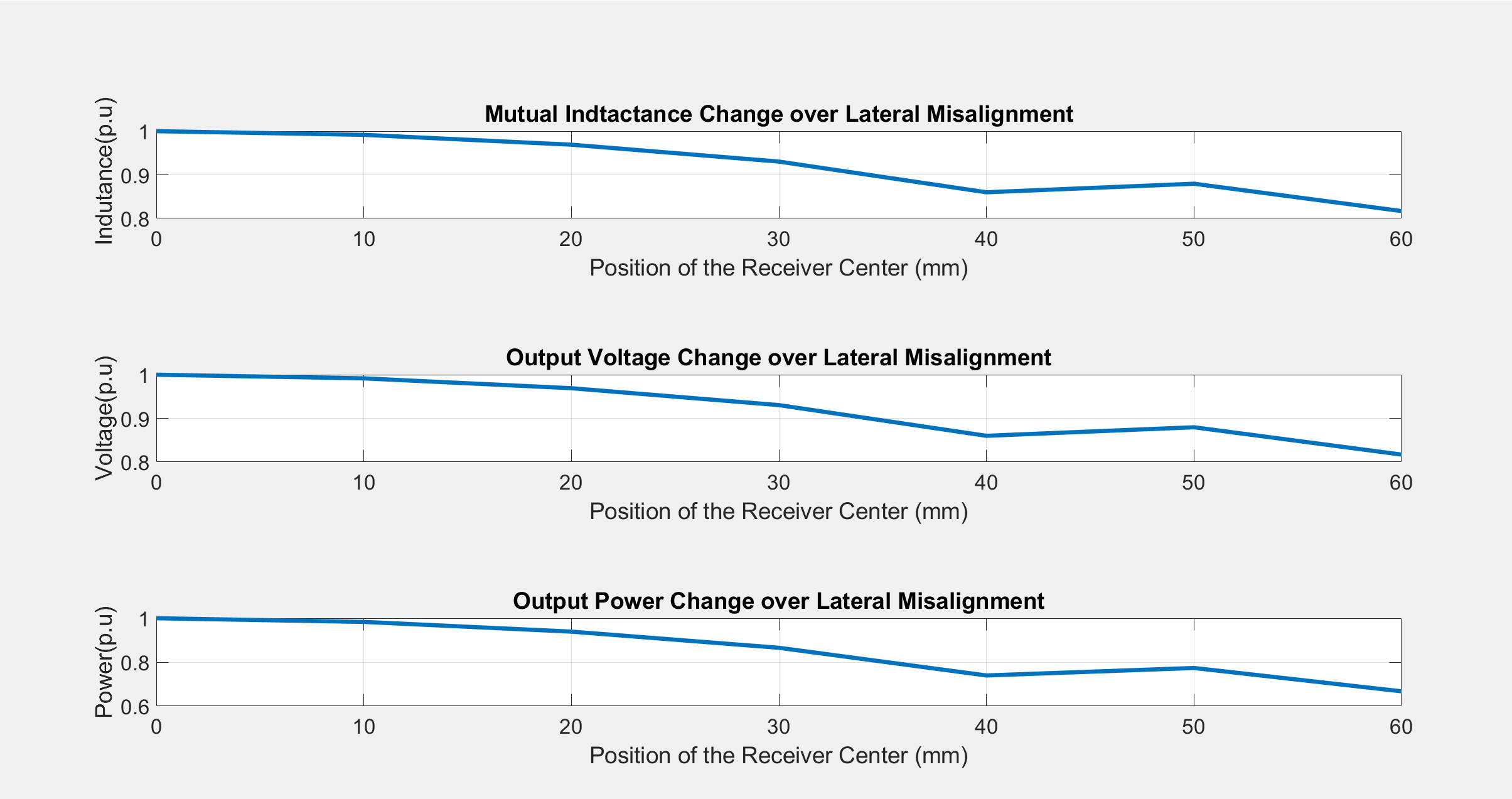


Figure Change on mutual inductance, output power and voltage over angular misalignment

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.

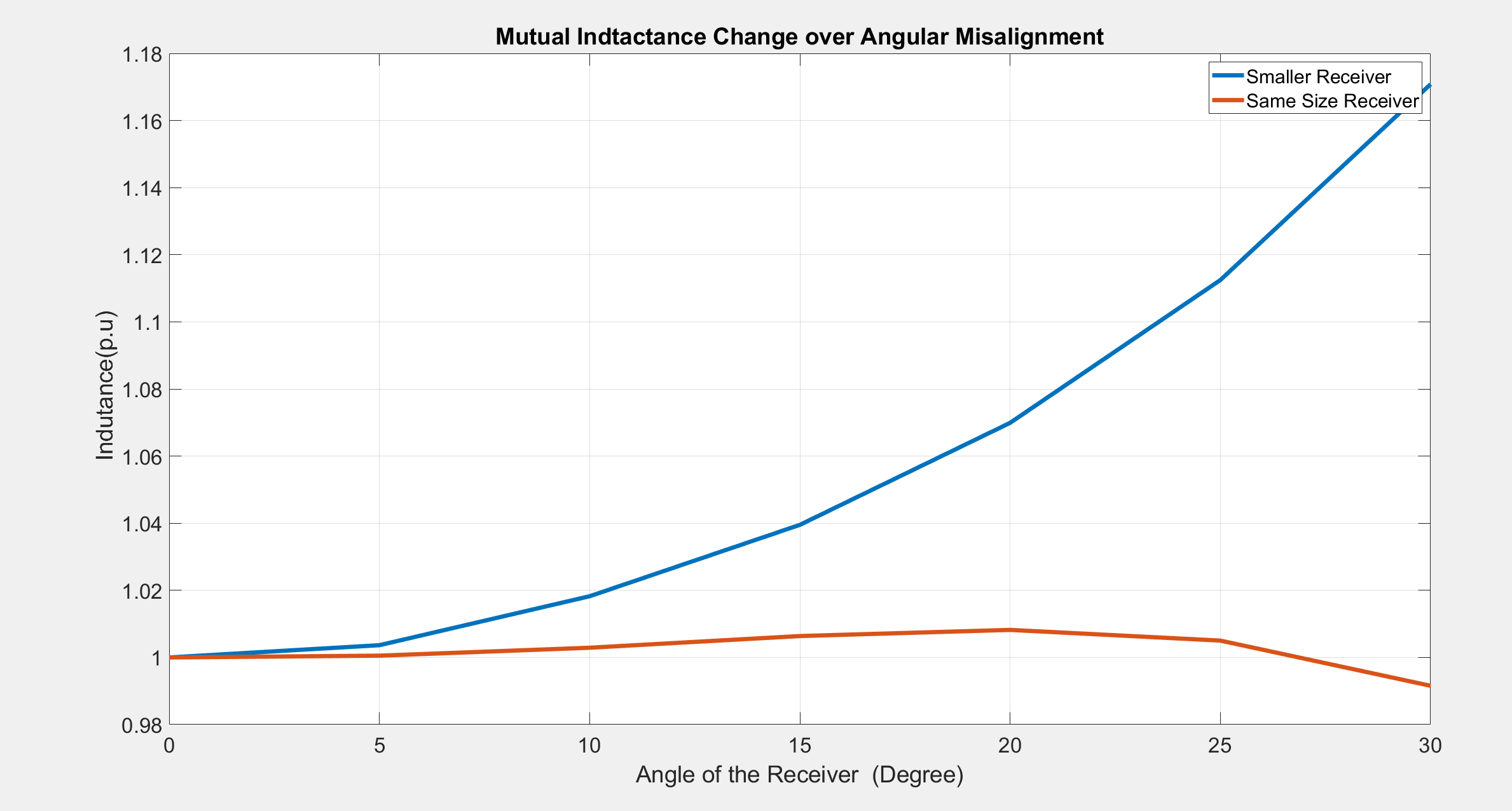


Figure Change on mutual induction over angular misalignment

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.

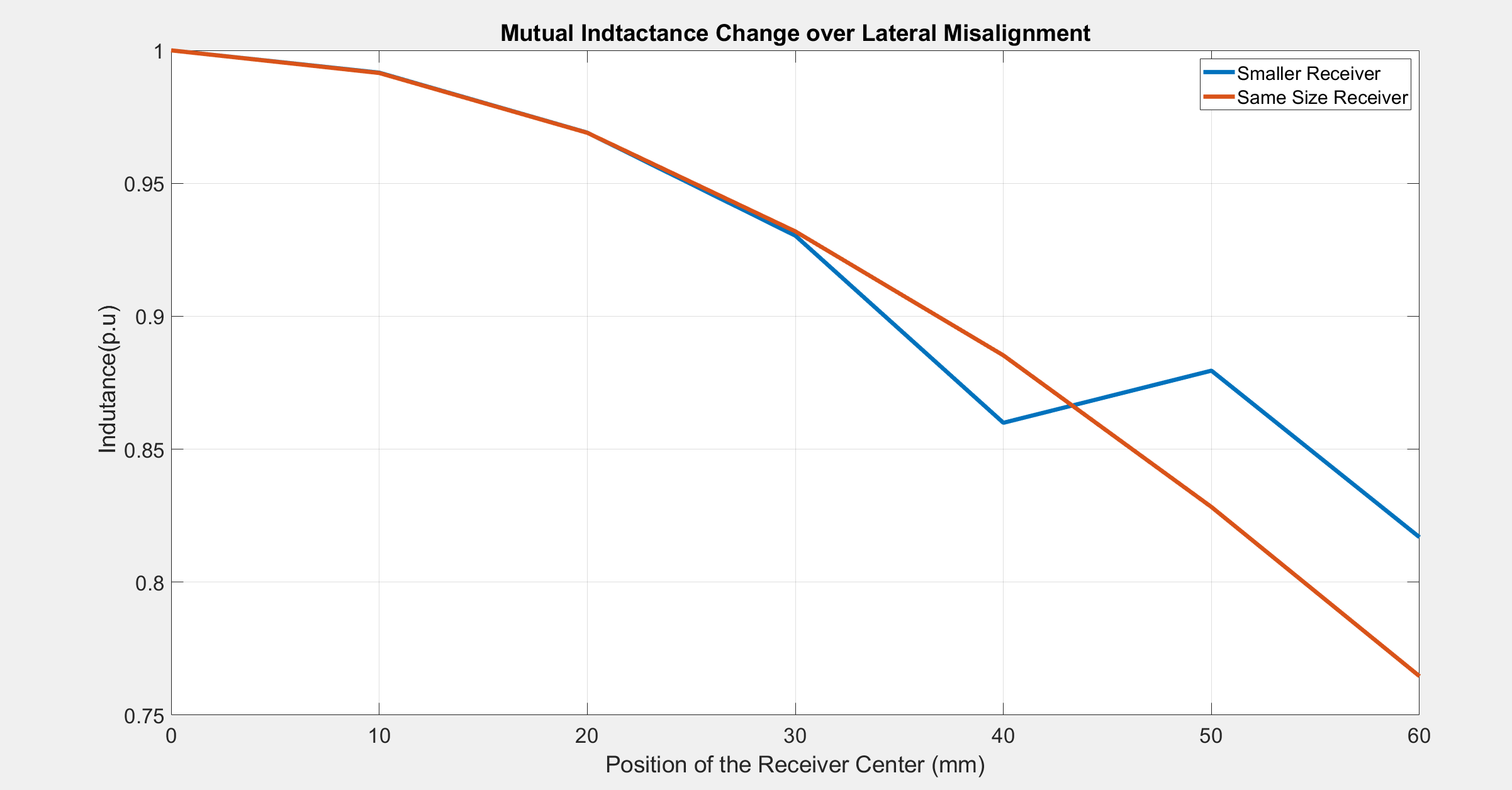


Figure Change on mutual induction over lateral misalignment

# 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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# References

[1] J. C. Schuder, J. H. Gold and H. E. Stephenson, "An Inductively Coupled RF System for the Transmission of 1 kW of Power Through the Skin," in IEEE Transactions on Biomedical Engineering, vol. BME-18, no. 4, pp. 265-273, July 1971, doi: 10.1109/TBME.1971.4502849.

[2] J. G. Bolger, F. A. Kirsten, and L. S. Ng, “Inductive power coupling for an electric highway system,” in Proc. IEEE 28th Veh. Technol. Conf., 1978, vol. 28, pp. 137–144.

[3] J. G. Bum and B. H. Cho, “An energy transmission system for an artificial heart using leakage inductance compensation of transcutaneous transformer, ”IEEE Trans. Power Electron. , vol. 13, no. 6, pp. 1013–1022, Nov. 1998

[4] G. A. Covic, J. T. Boys, M. L. G. Kissin, and H. G. Lu, “A three-phase inductive power transfer system for roadway-powered vehicles,” IEEE Trans. Ind. Electron. , vol. 54, no. 6, pp. 3370–3378, Dec. 2007.

[5] H. Hao, G. A. Covic and J. T. Boys, "A Parallel Topology for Inductive Power Transfer Power Supplies," in IEEE Transactions on Power Electronics, vol. 29, no. 3, pp. 1140-1151, March 2014, doi: 10.1109/TPEL.2013.2262714.

[6] Wang, J.; Li, J.; Ho, S.L.; Fu, W.N.; Li, Y.; Yu, H.; Sun, M. Lateral and angular misalignments analysis of a new PCB circular spiral resonant wireless charger. IEEE Trans. Magn. 2012, 48, 4522–4525.

[7] Abou Houran, M.; Yang, X.; Chen, W. Magnetically Coupled Resonance WPT: Review of Compensation Topologies, Resonator Structures with Misalignment, and EMI Diagnostics. Electronics **2018**, 7, 296

[8] Jia Hou; Qianhong Chen; Siu-Chung Wong; Tse, C.K.; Xinbo Ruan. Analysis and control of series/series-parallel compensated resonant converter for contactless power transfer. IEEE J. Emerg. Sel. Top. Power Electron. 2015, 3, 124–136

[9] Lee, K.; Cho, D.H. Diversity analysis of multiple transmitters in wireless power transfer system. IEEE Trans. Magn. 2013, 49, 2946–2952.

[10] X. Meng, D. Qiu, B. Zhang and W. Xiao, "Output Voltage Stabilization Control without Secondary Side Measurement for Implantable Wireless Power Transfer System," 2018 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (Wow), Montréal, QC, 2018, pp. 1-5, doi: 10.1109/WoW.2018.8450927.

[11] S. Alshhawy, A. Barakat, K. Yoshitomi and R. K. Pokharel, "Separation-Misalignment Insensitive WPT System Using Two-Plane Printed Inductors," in IEEE Microwave and Wireless Components Letters, vol. 29, no. 10, pp. 683-686, Oct. 2019, doi: 10.1109/LMWC.2019.2935621.

[12] W. Dehui, S. Qisheng, W. Xiaohong, H. Tianfu, “Analytical calculation of mutual coupling between two misaligned rectangular coils with rectangular cross-section in wireless power applications” in Journal of Physics D: Applied Physics, vol.50, no.43, pp. 43LT06, Oct. 2017, doi: 10.1088/1361-6463/aa8ca3

[13] Z. Luo and X. Wei, "Mutual Inductance Analysis of Planar Coils with Misalignment for Wireless Power Transfer Systems in Electric Vehicle," 2016 IEEE Vehicle Power and Propulsion Conference (VPPC), Hangzhou, 2016, pp. 1-6, doi: 10.1109/VPPC.2016.7791733.

[14] X. Zhang, H. Meng, B. Wei, S. Wang and Q. Yang, "Mutual inductance calculation for coils with misalignment in wireless power transfer," in The Journal of Engineering, vol. 2019, no. 16, pp. 1041-1044, 3 2019, doi: 10.1049/joe.2018.8670.

[15] H. Polat, E. Ayaz, O. Keysan "Design of Modular Rotational Dynamic Inductive Power Transfer System," 2020 IEEE Wireless Power Transfer Conference (WPTC)