CONTACTLESS POWER TRANSFER SYSTEM- HARDWARE ANALYSIS

Presentation By Dr. Praveen Kumar
Associate Professor
Department of Electronics & Communication Engineering
Introduction

Computation of mutual inductance for square coils

Generalized computation of mutual inductance for coils of different geometries

Ongoing and future works
It is important to analyze the contactless system by developing a hardware prototype to check its real time functioning.

This presentation explains some hardware works in contactless system done at IITG and some glimpse of ongoing and future works.

The prototype of contactless system mainly involves the following factors, to perform power conversion tasks required at different stages.

1. The development of converters and controllers.
2. Design of compensation capacitors, filter capacitors and inductors.
In addition, the magnetic coupling of the coils mainly depends on mutual inductance (MI) between the coils.

Therefore, computation of MI is one of the crucial factor in the design of contactless system and will play a key role in determination of efficiency and power transferred.
Mutual inductance (MI) between two square coil
Mutual inductance (MI) between two square coil

- The analysis presented in this paper computes MI between two air core square coils, placed in a flat planar surface coinciding in space.
- The air core square coil has mutually coupled primary and secondary coil.
- The coil which is excited is referred as excitation coil (EC) and the coil where the output variations are observed is referred as observation coil (OC) as shown in Fig.1.

Fig.1. Block diagram of contactless system
As the MI of the coil varies with the change in position of the coils, different variations of the coils i.e. Misalignments are analyzed.

Different cases of variations of OC with respect to EC are taken into account, which are shown in Fig. 2.

Fig.2. Possible variations of contactless coil
Mutual inductance (MI) between two square coil (Contd.)

- The schematics of different variations of coil is shown in Fig. 3

Fig. 3. Schematics of square coils for analyzed variations (a) PA - Vertical variation (b) PA - Planar variation (c) LM - Horizontal variation (d) LM – Planar variation (e) Angular misalignment (f) Both lateral and angular misalignment.
Terminologies used to refer variation of square coil

- **Prefect alignment:** If EC and OC are placed in a flat planar surface with coinciding axes, such arrangement of coils is referred as *perfect alignment (PA)*.

- **Lateral misalignment:** If coils are situated in parallel plane and displaced horizontally, such arrangement of coils is referred as *Lateral misalignment (LM)*.

- **Angular misalignment:** If OC is titled up or down with certain angle (<90°) due to unequal surface impacts; such arrangement of coils is referred as *angular misalignment*.

- **Both lateral and angular misalignment:** If OC is both tilted and varied horizontally, such arrangement of coils is referred as *both lateral and angular misalignments*. 
The coil parameters used in Fig.3 is described in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC, OC</td>
<td>Excitation coil, observation coil</td>
</tr>
<tr>
<td>h</td>
<td>Deviated vertically from the center of the coil</td>
</tr>
<tr>
<td>d</td>
<td>Deviated horizontally from the center of the coil</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Angle of OC with respect to EC</td>
</tr>
</tbody>
</table>

Table I: Coil Parameters
The circuit topology of the inductive coils resembles an inductively coupled transformer, represented by an equivalent circuit shown in Fig. 4.

- \( I \) – supply current
- \( \lambda_1 \) – magnetic flux
- \( \lambda_{12} \) – mutual flux
- EC – Excitation coil
- OC – Observation coil
- \( V_o \) – Voltage across the secondary coil

Fig. 4. Equivalent circuit model of an inductive coil
MI between two coupled coils can be calculated from the basic expression as given by (1)

\[ M = \frac{\lambda_{12}}{I_1} \]  

The flux linked with the OC (\(\lambda_{12}\)) due to current in the EC can be calculated analytically by considering the flux distribution of each individual coil turns of the OC.

The area enclosed by the selected turn of OC is divided into small regions and thereby considering the complete spiral square coil.

The flux through each small region of the OC is taken into account to calculate the flux linked to OC due to EC.
A sequence of program routine have been used to carry out this process

The total flux linked in the OC is obtained by the sum of the flux linked in each small grid for all the turns of the OC.

Assuming $\varphi_n$ is the flux linked with the $n^{th}$ region of the area enclosed by single turn of the OC, then $\lambda_{12}$ can be estimated by (2).

$$\lambda_{12} = \sum \varphi_n$$  \hspace{1cm} (2)

The limit of the summation depends on the number of small regions formed in a single turn of OC.
The flux linked to each of these small regions of OC due to EC is calculated with the following assumptions.

i. The insulated coil conductors are placed such that there is no space between conductors of any two loop and they are touching each other.

ii. The magnetic field in the small region of the coil (Fig. 5) is assumed to be constant and its value is calculated at the center of the small region.

![Fig. 5. Square current carrying coil (a) Single turn (b) Single turn segmented (c) Multiple turn.](image)
Based on these assumptions, $\varphi_n$ for each small region is calculated using (3) and (4), which depends on the magnetic field at the center of the small region, $n^{th}$ area ($A_n$) and normal vector of the $n^{th}$ area ($\vec{B}_c$).

\[ A_n = \Delta x_n \cdot \Delta y_n \] (3)

\[ \varphi_n = \vec{B}_c \cdot (A_n \cdot \hat{A}_n) \] (4)

Where, $\Delta x_n$ and $\Delta y_n$ are the length and width of the small divided region as shown in Fig. 5(b).

The magnetic field ($\vec{B}_c$) at the center of the small region is caused due to EC.

($\vec{B}_c$) is calculated for $P$ turns of EC and is given by (5).

\[ \vec{B}_c = \sum_{m=1}^{P} \vec{B} \] (5)
The individual coil turns of EC is modeled by four straight current carrying conductors.

Let \( \mathbf{B} \) is the magnetic field due to one current carrying loop of EC as shown in Fig. 5(a) and is given by (6).

\[
B = \sum_{n=1}^{4} \mathbf{B}_n
\]  

(6)

In the above equation, \( n \) represents the four sides of the single current carrying loop.

The \( \mathbf{B}_1 \), \( \mathbf{B}_2 \), \( \mathbf{B}_3 \) and \( \mathbf{B}_4 \) are the magnetic fields of the sides of the square coil AB, BC, CD and DA.

\( \mathbf{B}_n \) can be calculated from the Bio-Savart law for magnetic field.
The basic magnetic field equation \( \vec{B}_n \) at any point in space due to a straight current carrying conductor is given by (7).

\[
\vec{B} = \int \frac{\mu_0 I \, ds \times \hat{R}}{4\pi R^2}
\]

(7)

Where, \( \hat{R} \) is the unit vector in the direction of position vector of the observation point, originating from the differential element of current carrying conductor \( ds \).

The direction of \( ds \) is in the direction of current in the conductor. The integration in (6) is performed over the length of the conductor.

Similarly, the magnetic field at a point in space and flux linkage calculations can be done for spiral square coils with multiple turns as shown in Fig. 5(c), where L and W are the length and width of the coil.
The procedure for numerical calculation is explained in the following steps.

i. The total number of turns for EC (P) and OC (Q) are determined.

ii. 3D co-ordinates of a single turn of EC and OC are determined.

iii. Diameter of conductor and distance between EC and OC (depending on the type of variation) is determined.

iv. The selected turn of the coil is divided into multiple small areas from $A_1.....A_n$ as shown in Fig. 5(b).

v. Calculate the total flux linked to each small area of OC using (8) by calculating the magnetic field at the center.

$$ \varphi_1 = \sum_{n=1}^{4} \frac{\mu_o}{4\pi} \int \frac{I ds \times \hat{R}}{R^2} \cdot (A \cdot \hat{A}) $$  (8)
The flux linked in a single turn \( \phi_m \) of OC is obtained by summing all the fluxes using (9).

\[
\phi_1 = \sum_{k=1}^{p} \sum (\phi_1 + \phi_2 + \ldots \phi_n) \tag{9}
\]

This procedure is repeated for all turns of EC and OC and \( \lambda_{12} \) is calculated using (10).

\[
\lambda_{12} = \sum_{m=1}^{Q} \phi_m \tag{10}
\]

Therefore from these equations MI is calculated using (1).

This procedure has been used for all variations of EC and OC with their corresponding new coordinates and vertices.
Thus, the method adapted in this work has used only Biot-Savart law for a straight current carrying conductor; which is the basic equation for calculating the magnetic field.
Flow chart describing numerical evaluation

Fig. 6. Flow chart describing numerical evaluation.
The commercial 3-D finite element tool ANSYS Maxwell 14.0.0 has been used for validating the analytical model.

The EC and OC considered in this work have 11 and 9 turns respectively.

The EC is excited with a current of 10A.

The EC and OC are modeled for different variations and are analyzed by changing their co-ordinates in simulation environment.

The models are created using the co-ordinates taken from the experimental setup.

The FEA models are formed for all the configurations of the coils and various positions of OC by changing its coordinates.
To simplify the analytical calculations and to reduce the computation time, following assumptions are made in this investigation for flux linkage calculations.

i. As the 3-D FEA model for spiral square coil takes very long time and sophisticated computation environment, the models are analyzed with all the dimensions reduced to one fifth of the original. This adjustment is justified as the variation of the flux linkage is linear with the dimension of the whole system, which can be proved analytically.

ii. To reduce the computational time, OC is put as a surface whose area is equal to that of EC and flux linked to the surface has been calculated.

iii. The multiple turns of EC and OC are assumed to be placed near with no space between the turns of the coils.
Fig. 7 shows the FEA models of the coils for different variations such as vertical, angular and planar.

The flux linked in the OC due to EC is found by integrating the magnetic field over the area of OC using Maxwells field calculator.

*Fig. 7. FEA models of square coils for different variations (a) Vertical (b) Angular (c) Planar.*
Fig. 8 shows the 2D plot of magnetic field lines of EC and OC having four conductors each.

Fig. 8(a) shows two positions of vertical variation of OC at small and large distances. Fig. 8(b) shows two positions of angular variation of OC at 0° and 45° angles.
In order to verify the analytical and FEA results an experimental setup is built in the laboratory.

Table II shows the specifications of the components used for evaluation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{dc}$</td>
<td>DC supply</td>
<td>0-30V</td>
</tr>
<tr>
<td>$L_p$</td>
<td>Inductance of EC</td>
<td>54μH</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Inductance of OC</td>
<td>37μH</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
<td>18kHz</td>
</tr>
<tr>
<td>$C_f$</td>
<td>Filter capacitor</td>
<td>1.44μF</td>
</tr>
<tr>
<td>$W$</td>
<td>Width of the coil</td>
<td>18cm</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of the coil</td>
<td>18cm</td>
</tr>
<tr>
<td>$N_p$</td>
<td>Number of turns in EC</td>
<td>11</td>
</tr>
<tr>
<td>$N_s$</td>
<td>Number of turns in OC</td>
<td>9</td>
</tr>
</tbody>
</table>
The circuit topology and its control blocks are shown in Fig. 9 and Fig. 10.

The filter capacitor has been calculated using the formula given by (11).

\[ C_f = \frac{1}{\omega^2 L_p} \]  

Fig. 9. Schematic representation of power circuit.

Fig. 10. Controller blocks.
The details of experimental setup for different variations are briefly explained below:

i. For vertical variation, the arrangement in wooden staff is made to vary the distance between OC and EC.

ii. For planar variation, the whole supporting system of wooden staff is rotated in a circle around EC.

iii. For lateral variation, the wooden staff arrangement is made such that OC can be moved over the wooden staffs horizontally.

iv. For angular misalignment, OC is fixed in a supporting rod above EC at a vertical height and tilted.
Fig. 11 shows the complete hardware arrangement made for the experimental evaluation of MI.

The schematics of different variations are shown in Fig. 12.
The conductors of the coils are placed such that there is no space between the conductors of any two loop and they are not touching each other.

The conductors are spread in a distance of 1.98cm and 1.65cm for EC and OC. The inner area which is not occupied by the conductor is 197.12cm² and 216.27cm² for EC and OC respectively.

The experimental setup built is made to analyze all possible position of the coil including lateral and angular misalignments.

The formula used for experimental computation of MI is given by

$$MI = \frac{V_{OC}}{V_{EC}} L_p$$  \hspace{1cm} (12)
The numerical results obtained from three analysis such as analytical method, finite element model and an experimental setup has been analyzed and compared.

In order to compare the results, this study has considered the following general points:

i. Maximum and minimum variations of vertical distance between EC and OC have been taken as 10cm and 2 cm.

ii. Maximum and minimum variation in horizontal direction have been taken as 11.4cm and 0cm.

iii. The maximum rotational variation considered is $90^\circ$. This is because the MI value would be repetitive for square geometry for angle beyond $90^\circ$.

iv. The vertical and horizontal distances are increased by 1cm for subsequent observations.

v. The planar variation is recorded for a sequence of angles at an interval of $10^\circ$ while, due to practical constraints the experimental readings are recorded for a step of $15^\circ$ change.
**Perfect Alignment - Vertical and Planar Variation**

- Fig. 13 and Fig. 14 shows the graphical plots of perfectly aligned curve with vertical and planar variation.
Lateral Misalignment - Horizontal and Planar Variation

- Fig. 15 and Fig. 16 shows the graphical plots of Lateral Misalignment with horizontal and planar variation.
Angular Misalignment, Both Lateral and Angular Misalignment

Fig. 17 and Fig. 18 show the graphical plots of angular misalignment and both lateral and angular misalignment.

Fig. 17. Angular misalignment - angular variation

Fig. 18. Both lateral and angular misalignment (Angle=10°, 20°, 30°).
Consider two square coils of length and width of 18cm having a conductor diameter of 1.83mm.

The number of turns for excitation (EC) and observation coils (OC) are 11 and 9. The current flow in EC is taken to be 10A.

The following cases of variations are chosen for explanation of analytical model.

Case I: Perfect alignment - vertical variation: OC kept at a vertical height of 2cm with respect to EC.

Case II: Perfect alignment - planar variation: OC kept at vertical height of 2.1cm and rotated with an angle of 10°.

Case II: Perfect alignment - planar variation: OC kept at vertical height of 2.1cm and rotated with an angle of 10°.
Mutual inductance (MI) between two square coil (Contd.)

- The numerical values obtained in each step for multiple turns of OC are summarized in Table VIII for the above considered cases.
- The flux linkage for each turn of OC is calculated using (8) and (9).
- From these results, the total flux linkage and mutual inductance is calculated using (10) and (1).

Table III
Results of sample calculation

<table>
<thead>
<tr>
<th></th>
<th>Case I (μWb)</th>
<th>Case II (μWb)</th>
<th>Case III (μWb)</th>
<th>Case I (μWb)</th>
<th>Case II (μWb)</th>
<th>Case III (μWb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ₁</td>
<td>20.78</td>
<td>19.72</td>
<td>3.27</td>
<td>φ₆</td>
<td>20.03</td>
<td>18.87</td>
</tr>
<tr>
<td>φ₂</td>
<td>20.81</td>
<td>19.69</td>
<td>3.18</td>
<td>φ₇</td>
<td>19.60</td>
<td>18.49</td>
</tr>
<tr>
<td>φ₃</td>
<td>20.76</td>
<td>19.59</td>
<td>3.10</td>
<td>φ₈</td>
<td>19.09</td>
<td>18.04</td>
</tr>
<tr>
<td>φ₄</td>
<td>20.61</td>
<td>19.42</td>
<td>3.01</td>
<td>φ₉</td>
<td>18.49</td>
<td>17.52</td>
</tr>
<tr>
<td>φ₅</td>
<td>20.37</td>
<td>19.18</td>
<td>2.92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>λ₁₂</td>
<td>180.50</td>
<td>170.50</td>
<td>26.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>18.05μH</td>
<td>17.05μH</td>
<td>2.62μH</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The following conclusions are drawn from the work:

i. When the coils are placed close to each other with coinciding axes, MI values are maximum; which indicates high coupling between the coils and expected to have maximum power transfer in contactless systems.

ii. At large coil distances, relatively large horizontal and vertical misalignments; MI have no significant effects. This indicates relatively low coupling and it would not transfer any power.

iii. In planar variation, MI value would vary marginally. Such type of variation would not affect the power transfer in contactless systems.

iv. In angular misalignment, tilting OC at certain angle brings half of the coil closer to the perimeter of EC and due to this MI value increases and for other angles, MI values would suddenly decrease. Such type of variations in practical systems would cause instability.
Mutual inductance for coils of different geometries
In this work, generalized semi analytic computation method for MI has been explained for different coil geometries.

Coil geometries such as rectangle, circle, ellipse, hexagon and pentagon have been used.

The coil geometries analyzed in this work is depicted in Fig. 19.

Fig. 19. Schematics of spiral arrangement of different coil geometries (a) rectangular (b) circular (c) elliptical (d) hexagonal (e) pentagonal.
The MI of two coupled coils can be calculated from the basic expression as given by (1).

Here, the technique used for calculating $\lambda_{12}$ for different coil geometries is different from the former computation.

$\lambda_{12}$ linked to the SC due to PC is calculated semi-analytically based on the discretization of individual coil turns of SC due to PC.

A computer program routine used which automatically divides the interior of the coil geometries into *triangular elements* with specifications of the basic parameter defining the geometry of the coil.
The flux \( \varphi_i \) crossing through the \( i^{th} \) triangular element is given by (13).

\[
\varphi_i = \left( \vec{B}_{\text{cent}} \right)_i \cdot \left( \vec{A}_i \cdot \vec{A}_i \right) \tag{13}
\]

Where, \( i \) varies from 1 to \( Q \), \( Q \) is the number of discretized triangular element present in the single turn of the coil. \( \vec{A}_i \) is the area of the \( i^{th} \) triangular element. \( \vec{A}_i \) is the normal vector perpendicular to the plane of the \( i^{th} \) area.

\( \left( \vec{B}_{\text{cent}} \right)_i \) and \( \vec{A}_i \) are calculated from the coordinates of the vertices of the triangular element obtained from automatic mesh generation.

\( \vec{A}_i \) is the magnetic field at the center of the \( i^{th} \) single triangular element caused due to PC.
Considering a PC of $M$ number of turns and $N$ number of straight conductors in each turn, then at the center of the triangular element is calculated by (14).

$$\left( \overline{B}_{cent} \right)_i = \sum_{m=1}^{M} \sum_{n=1}^{N} \overline{B}_{cond}$$ (14)

Here, $M$ and $N$ denotes number of turns in PC and number of straight current carrying conductor in a single turn of PC.

The magnetic field due to a single straight current carrying conductor is calculated by Biot-Savart law (4).

$$\overline{B}_{cond} = \frac{\mu_0 I}{4\pi R} \left( \sin \varphi_1 + \sin \varphi_2 \right)$$ (15)

The magnetic field due to whole PC at the center of the triangular element is given by (16).

$$\left( \overline{B}_{cent} \right)_i = \sum_{m=1}^{M} \sum_{n=1}^{N} \frac{\mu_0 I}{4\pi R} \left( \sin \varphi_1 + \sin \varphi_2 \right)$$ (16)
R is the perpendicular distance from the center of the triangular element (P) from the current carrying conductor. L is the length of the conductor, $\phi_1$ and $\phi_2$ are the geometrical angles and $\phi$ is the angle made by the differential element dl as shown in Fig. 20.

Fig. 20. Magnetic field due to a straight current carrying conductor.
The number of straight current carrying conductor \( N \), used in (16) would vary for different coil geometry as given by (17). However, (16) is applicable only for straight current carrying conductor.

\[
N = \begin{cases} 
4, & \text{rectangular coil} \\
6, & \text{hexagonal coil} \\
5, & \text{pentagonal coil}
\end{cases}
\]  

(17)

To calculate the magnetic field due to circular and elliptical coils, these coil geometries are approximated with many small straight conductors and then expression (16) has been applied.

A single turn of the circular coil approximated with multiple straight conductors such as \( x_0-x_1, x_1-x_2, x_2-x_3, \ldots x_{11}-x_0 \).
Fig. 21. shows the single turn of meshed hexagonal coil and approximation of single circular coil with multiple straight conductors.
Semi analytic computation method (contd.)

- The \( \overrightarrow{B}_{\text{cent}} \) obtained from (16) is used to calculate the flux crossing at the center of the triangular element.

- In similar manner, the flux crossing through all the triangular elements can be calculated and the total flux linked \( (\varphi_n) \) to a single turn of the SC is given by (18).

\[
\varphi_n = \sum \varphi_1 + \varphi_2 + \ldots + \varphi_Q \quad (18)
\]

- By following the procedure explained from (13)-(18), the total flux linked to all the turns of the SC for a particular position is calculated, which is given by (19).

\[
\lambda_{12} = \sum_{j=1}^{p} \sum_{n=1}^{Q} \varphi_n \quad (19)
\]

- In this manner, MI is calculated for different misaligned cases of coil geometry using equations (13) - (19).
Automatic mesh generation

- Automatic mesh generating method is adapted for discretizing the coils of any geometry having curved surface and corners.
- In such cases, regular grid division may not be suitable, creating this type of mesh will result in a fatal error.
- The program routine used in this work adopts an automatic mesh generation method [3], which considers every single turn of SC and discretize it into triangular elements as shown in Fig. 21.
- The selected coil turn of SC is first subdivided into quadrilateral block. The coordinates describing each block and the block topologies are specified as input data.
- Each block is represented by an eight-node quadratic isoparametric element with its local coordinate system.
The local coordinate system \((\alpha, \beta)\), is represented in terms of global coordinate system \((x, y)\) as given by (20) and (21).

\[
x(\alpha, \beta) = \sum_{i=1}^{8} \psi_i(\alpha, \beta)x_i \quad (20)
\]

\[
y(\alpha, \beta) = \sum_{i=1}^{8} \psi_i(\alpha, \beta)y_i \quad (21)
\]

Where, \(\psi_i(\alpha, \beta)\) is a shape function associated with node \(i\) and \((x_i, y_i)\) are the coordinates of node \(i\) defining the boundary of the quadrilateral block formed at the solution region.

The obtained quadrilateral block is divided into quadrilateral elements.

The size of the quadrilateral elements depends on the number of element subdivisions \((N_\alpha\) and \(N_\beta)\) in \(a\) and \(b\) directions and weighting factors \((W_\alpha)_i\) and \((W_\beta)_i\).

The specification of weighting factors is required for allowing graded mesh within a block.
The initial $a$ and $b$ values are taken to be -1, so that the natural coordinates are incremented according to (22) and (23).

\[
\alpha_i = \alpha_i + \frac{2(W_{\alpha})_i}{W_{\alpha}^T} \quad W_{\alpha}^T = \sum_{j=1}^{N_t} (W_{\alpha})_j \quad (22)
\]

\[
\beta_i = \beta_i + \frac{2(W_{\beta})_i}{W_{\beta}^T} \quad W_{\eta}^T = \sum_{j=1}^{N_\eta} (W_{\eta})_j \quad (23)
\]

Further, each quadrilateral element is divided into two triangular elements.

This subdivision is done across the shortest diagonal of the quadrilateral element.

The detailed explanation and an illustration of the evaluation procedure has been explained later.
An image of different coils used for experimental verification is shown in Fig. 22. The values of $L_p$, $L_s$ and $C_f$ for different coil geometries are given in Table IV.
The values of $L_p$, $L_s$ and $C_f$ for different coil geometries are given in Table IV and dimensions of the coils is shown in Table V.

<table>
<thead>
<tr>
<th>Type of coil geometry</th>
<th>$L_p$ ($\mu$H)</th>
<th>$L_s$ ($\mu$H)</th>
<th>$C_f$ ($\mu$F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangle</td>
<td>34.366</td>
<td>34.55</td>
<td>2.27</td>
</tr>
<tr>
<td>Circle</td>
<td>36.222</td>
<td>36.84</td>
<td>2.16</td>
</tr>
<tr>
<td>Ellipse</td>
<td>26.744</td>
<td>26.77</td>
<td>2.92</td>
</tr>
<tr>
<td>Hexagon</td>
<td>30.472</td>
<td>28.92</td>
<td>2.56</td>
</tr>
<tr>
<td>Pentagon</td>
<td>32.178</td>
<td>32.17</td>
<td>2.43</td>
</tr>
</tbody>
</table>

Table IV
Specifications of inductance and capacitance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of copper strip</td>
<td>0.83mm</td>
</tr>
<tr>
<td>Diameter of copper</td>
<td>1.83mm</td>
</tr>
<tr>
<td>Width of the total turn</td>
<td>1.98cm</td>
</tr>
<tr>
<td>Copper track seperation</td>
<td>0.008mm</td>
</tr>
<tr>
<td>Total length of the coil</td>
<td>5m</td>
</tr>
<tr>
<td>Number of turns in PC</td>
<td>10</td>
</tr>
<tr>
<td>Number of turns in SC</td>
<td>10</td>
</tr>
</tbody>
</table>

Table V
Dimensions of the coil
Results and Discussion

- Comparison of graphical plots between analytical method and experimental setup has been summarized. The results of five different coil geometries such as rectangular, circular, elliptical, hexagonal and pentagonal coils are discussed.

- **Rectangular coil geometry** Fig. 23 and 24 shows the comparison of graphical plots of rectangular coil geometry for different misalignments.

![Graphs showing comparison of misalignments](image-url)
Circular coil geometry

Fig. 24 and 25 shows the comparison of graphical plots of circular coil geometry for different misalignments.

Fig. 24: Circular coil - vertical and lateral misalignment

Fig. 25: Circular coil - planar and angular misalignment.
Elliptical coil geometry

- Fig. 26 and 27 shows the comparison of graphical plots of elliptical coil geometry for different misalignments.

Fig. 26. Elliptical coil- vertical and lateral misalignment

Fig. 27: Elliptical coil - planar and angular misalignment.
Hexagonal coil geometry

- Fig. 28 and 29 shows the comparison of graphical plots of Hexagonal coil geometry for different misalignments.

![Graph 1: Hexagonal coil - vertical and lateral misalignment](image1)

- Lateral Misalignment (LM)
- Vertical Misalignment (VM)

![Graph 2: Hexagonal coil - planar and angular misalignment](image2)

- Planar Misalignment (PM)
- Angular Misalignment (AM)

Fig. 28: Hexagonal coil - vertical and lateral misalignment

Fig. 29: Hexagonal coil - planar and angular misalignment.
Results and Discussion (cont.)

Pentagonal coil geometry

- Fig. 30 and 31 shows the comparison of graphical plots of pentagonal coil geometry for different misalignments.

Fig. 30. Pentagonal coil - vertical and lateral misalignment

Fig. 31. Pentagonal coil - planar and angular misalignment.
Comparison of change in MI

- Table VI shows percentage change in the values of MI for VM and LM between two values of initial and final position.
- In LM case rectangular coil shows the smallest change in MI value, when SC is moved from initial to final position and is most suited for lateral variation.
- It can be seen from the results that in case of PM, circular coil geometries shows greatest tolerance due to its regular geometry.
- The variation of AM of the coils has same pattern and the MI values are less as the experiment is performed at larger distance for all the coil geometries.

<table>
<thead>
<tr>
<th></th>
<th>Rectangular</th>
<th>Circular</th>
<th>Elliptical</th>
<th>Hexagonal</th>
<th>Pentagonal</th>
</tr>
</thead>
<tbody>
<tr>
<td>VM(%)</td>
<td>85.43</td>
<td>83.15</td>
<td>90.14</td>
<td>84.81</td>
<td>83.29</td>
</tr>
<tr>
<td>LM(%)</td>
<td>58.77</td>
<td>73.26</td>
<td>89.44</td>
<td>88.72</td>
<td>74.83</td>
</tr>
</tbody>
</table>
Illustration of evaluation procedure

- To explain the computation procedure, circular coil geometry is chosen of radius 9cm.

- **Step I:** The circular solution region is defined using 21 nodes as shown in Fig. 32.

- The coordinates of the nodes (N) are obtained using the radius of the circle and are given in the Table VII.

- This circular solution region is divided into four quadrilateral isoparametric blocks each having eight nodes as shown in Table VIII.

**Table VII: Coordinates of the node**

<table>
<thead>
<tr>
<th>N</th>
<th>x</th>
<th>y</th>
<th>N</th>
<th>x</th>
<th>y</th>
<th>N</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>9.00</td>
<td>0.00</td>
<td>h</td>
<td>-8.31</td>
<td>3.44</td>
<td>o</td>
<td>6.36</td>
<td>-6.36</td>
</tr>
<tr>
<td>b</td>
<td>8.31</td>
<td>3.44</td>
<td>i</td>
<td>-9.00</td>
<td>0.00</td>
<td>p</td>
<td>8.31</td>
<td>-3.44</td>
</tr>
<tr>
<td>c</td>
<td>6.36</td>
<td>6.36</td>
<td>j</td>
<td>-8.31</td>
<td>-3.44</td>
<td>q</td>
<td>4.50</td>
<td>0.00</td>
</tr>
<tr>
<td>d</td>
<td>3.44</td>
<td>8.31</td>
<td>k</td>
<td>-6.36</td>
<td>-6.36</td>
<td>r</td>
<td>0.00</td>
<td>4.50</td>
</tr>
<tr>
<td>e</td>
<td>0.00</td>
<td>9.00</td>
<td>l</td>
<td>-3.44</td>
<td>-8.31</td>
<td>s</td>
<td>-4.50</td>
<td>0.00</td>
</tr>
<tr>
<td>f</td>
<td>-3.44</td>
<td>8.31</td>
<td>m</td>
<td>0.00</td>
<td>-9.00</td>
<td>t</td>
<td>0.00</td>
<td>-4.50</td>
</tr>
<tr>
<td>g</td>
<td>-6.36</td>
<td>6.36</td>
<td>n</td>
<td>3.44</td>
<td>-8.31</td>
<td>u</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Table VIII: Nodes of the quadrilateral block**

<table>
<thead>
<tr>
<th>Block</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>a-b-c-d-e-f-g-h-i-s-u-r-q-a</td>
</tr>
<tr>
<td>II</td>
<td>a-p-o-n-m-t-u-q-a</td>
</tr>
<tr>
<td>III</td>
<td>i-j-k-l-m-t-u-s-i</td>
</tr>
<tr>
<td>IV</td>
<td>e-f-g-h-i-s-u-r-e</td>
</tr>
</tbody>
</table>

Fig. 32. Circular solution region
(a) Subdivided solution region (b) single quadrilateral block describing coordinates at eight points.
Results and Discussion (contd.)

- **Illustration of evaluation procedure (contd.,)**
  - Local coordinate \((LC(\alpha, \beta))\) system corresponding to the global coordinates \((GC(x, y))\) for each node is defined and is given in Table IX.
  - **Step 2:** This step involves subdivision of the quadrilateral block into elements, considering \(N_\alpha\) and \(N_\beta\) to be 5. For convenience, \((W_\alpha)_i\) and \((W_\beta)_i\) are taken to be 1.
  - Fig. 33 shows the subdivided quadrilateral elements, where 1 to 36 represents the nodes of the quadrilateral elements.
  - In which, the results of 10 node obtained from the program for \(GC\) and \(LC\) is shown in Table X.

![Fig. 33: Meshed quadrilateral block](image-url)

<table>
<thead>
<tr>
<th>N</th>
<th>GC (cm)</th>
<th>LC N</th>
<th>GC</th>
<th>LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>(\alpha)</td>
<td>(\beta)</td>
<td>x</td>
</tr>
<tr>
<td>k</td>
<td>-6.36</td>
<td>-6.36</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>j</td>
<td>-8.31</td>
<td>-3.44</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>i</td>
<td>-9.00</td>
<td>0.00</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>s</td>
<td>-4.50</td>
<td>0.00</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

![Table IX: Global and local coordinate](image-url)

<table>
<thead>
<tr>
<th>N</th>
<th>GC (cm)</th>
<th>LC N</th>
<th>GC</th>
<th>LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>(\alpha)</td>
<td>(\beta)</td>
<td>x</td>
</tr>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>-1.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>2</td>
<td>-1.80</td>
<td>0.00</td>
<td>-0.6</td>
<td>-1.0</td>
</tr>
<tr>
<td>3</td>
<td>-3.60</td>
<td>0.00</td>
<td>-0.2</td>
<td>-1.0</td>
</tr>
<tr>
<td>4</td>
<td>-5.40</td>
<td>0.00</td>
<td>0.2</td>
<td>-1.0</td>
</tr>
<tr>
<td>5</td>
<td>-7.20</td>
<td>0.00</td>
<td>0.6</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

![Table X: GC and LC for nodes of quadrilateral element](image-url)
Illustration of evaluation procedure (contd.)

- Fig. 34 shows the division of each quadrilateral element into 50 triangular elements.
- Table VIII has shown the node numbers of only 10 triangular element as an example.
- Step 3: A single triangular element having node numbers 1, 2 and 8 (element number 1 in Fig. 33) is considered as shown in Fig. 34.
Illustration of evaluation procedure (contd.)

- The coordinates of the chosen triangular element is taken from Table VII are \((x_1, y_1, z_1)\) is \((0, 0, 0.02)\), \((x_2, y_2, z_2)\) is \((-0.018, -2.3 \times 10^{-5}, 0.02)\) and \((x_3, y_3, z_3)\) is \((-0.01806, -0.01812, 0.02)\).

- As the secondary coil is placed at a height of 2cm, the \(z\) coordinate is taken as 0.02m.

- Using this coordinates, the \(A_1\), \(A_1\) and \((\overrightarrow{B_{cent}})_1\) are calculated using (14).

- The values of \(A_1\), \(A_1\) and \((\overrightarrow{B_{cent}})_1\) are given below.

\[
\varphi_1 = 1.13 \times 10^{-7} \text{wb} \quad \overrightarrow{A_1} = 0 \hat{x} + 0 \hat{y} + 1 \hat{z} \quad A_1 = 1.6308 \times 10^{-4} \text{m}^2
\]

- On substituting these values, the flux \(\varphi_1\) crossing through the triangular element is calculated by (13) as given below:

\[
(\overrightarrow{B_{cent}})_1 = -3.33 \times 10^{-5} \hat{x} - 1.69 \times 10^{-5} \hat{y} + 6.9082 \times 10^{-4} \hat{z}, \text{wb/m}^2
\]
Illustration of evaluation procedure (contd.)

- In similar way, the flux crossing through all the surfaces of the triangular elements are calculated and added together to get the flux crossing through one turn of the secondary coil by (18).
- Table IX shows the flux linkage ($\varphi_n$) value of all the turns of circular secondary coil. $4.08 \times 10^{-5}$
- In order to obtain the total flux linked to the secondary coil ($\lambda_{12}$), the above said procedure is repeated for all the turns of the secondary coil using (19).
- $\lambda_{12}$ value is the summation of ($\varphi_n$) which is given by
- By substituting this value MI value is calculated as $4.08 \times 10^{-6}$, using the formula given in (1).
### Illustration of evaluation procedure (contd.)

<table>
<thead>
<tr>
<th>Turn</th>
<th>Flux $\left(10^{-6} Wb\right)$</th>
<th>Turn</th>
<th>Flux $\left(10^{-6} Wb\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn 1</td>
<td>4.26</td>
<td>Turn 6</td>
<td>6.409</td>
</tr>
<tr>
<td>Turn 2</td>
<td>4.24</td>
<td>Turn 7</td>
<td>4.03</td>
</tr>
<tr>
<td>Turn 3</td>
<td>4.22</td>
<td>Turn 8</td>
<td>3.96</td>
</tr>
<tr>
<td>Turn 4</td>
<td>4.18</td>
<td>Turn 9</td>
<td>3.89</td>
</tr>
<tr>
<td>Turn 5</td>
<td>4.14</td>
<td>Turn 10</td>
<td>3.80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Flux ($\lambda_{12}$)</th>
<th>$4.08 \times 10^{-5} Wb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MI</td>
<td>$4.08 \times 10^{-6} H$</td>
</tr>
</tbody>
</table>

**Table XII: Flux linkage Calculation**
A 2 kw hardware prototype of contactless charging system is planned to develop in our lab to check G2V and V2G process, which is already on the process of development.

H-Bridge converter and resonant converters will be build in our lab shortly with different types of controllers such as spartan 3E FPGA board, kiel Microprocessor kit, sliding mode, adaptive sliding mode controller etc to check its robustness of controlling contactless coils.

Effect of compensation topologies in contactless system with respect to variations in frequency, load resistance and efficiency is going to be checked very shortly.
