ABSTRACT

Systems for contactless recharging have been developed to allow safe and flexible power transmission for electric automobiles. The anxiety associated with driving range may be considerably decreased by enhancing the viability of electric vehicle inductive charging systems as a whole. This study compares the features of round and square power pads for EV contactless charging systems. For the physical dimensions of these power pads, the Society of Automotive Engineers (SAE) suggested standard J2954. Parameters like as coupling coefficient as well as mutual inductance are analysed by imparting vertical and horizontal alignment to each kind of power pads. An interesting comparison has been presented by simulation of the power pads using ANSYS Electronics desktop and twin builder. In contrast, variable misalignment between two coils is has been utilised for analysis in dynamic computations of the coils' self and mutual inductance. This makes sweeping analysis easier and speeds up the computation. Impedance matching connections have been used on all three ports to tune the system at 51.3 kHz frequency for peak effectiveness. The greatest attainable efficiency for each coil prototype is calculated (through modelling and testing) and the results are compared. The importance of EMF software in designing a planar passive basis for WPT system has been explored. Overall, the suggested passive base coil approach has been shown to succeed in increasing the alignment between pads. It is also demonstrated that the mutual inductance reduces as misalignment increases, and vice versa.

Keywords: Wireless Power Transfer, WPT, ANSYS, Maxwell, SAE.
Figure 1 describes simplified circuit of a series-series (SS) architecture WPT system. Voltage at high frequencies does have an advantage over rest is small size of compensating capacitor as well as coil. As a consequence, the low-frequency main voltage is converted to a high-frequency voltage and supplied to a primary circuit. This is similar to transformer action and leads to high frequency magnetic field. This field links with secondary coil, inducing a high voltage frequency across its winding terminals. This induced voltage is influenced by the coils' coupling coefficient. Finally, the alternating voltage in its secondary winding is mended before being delivered to the load.

\[
Z_{T1} = Z_{C1} + Z_{R1} + Z_{L1} = \frac{1}{jwC_1} + R_1 + jwL_1
\]

\[
Z_{T2} = Z_{C2} + Z_{R2} + Z_{L2} = \frac{1}{jwC_2} + R_2 + R_L + jwL_2
\]

At resonance,
\[
Z_{C1} + Z_{L1} = 0 \quad \text{and} \quad Z_{C2} + Z_{L2} = 0
\]

where, \(I_2 = \frac{jwM}{R_2 + R_L} \times I_1\).

Input power delivered
\[
P_{in} = V_1I_1 = \frac{R_1 \times (R_2 + R_L) + (wM)^2}{R_2 + R_L} \times I_1^2
\]

And output power
\[
P_{out} = I_2^2R_L = \frac{w^2M^2I_1^2}{(R_2 + R_L)^2}
\]

Power efficiency
\[
\eta = \frac{P_{out}}{P_{in}} = \frac{R_L \times (wM)^2}{(R_2 + R_L) \times [R_1 \times (R_L + R_2) + (wM)^2]}
\]

Neglecting R_2 as it is very less than R_L.

\[
\eta = \frac{1}{(wM)^2}
\]

3. DESIGN OF THE COIL PARAMETERS

Plane planner spiral coils having good coupling coefficient and quality factor, hence used for wireless power transfer.

\[
D_{max} = D_{min} + (2N - 1)(S + W) + 2W
\]

\[
B = \frac{D_{max} - D_{min}}{D_{max} + D_{min}}
\]
The distance between two turns should be calculated by considering following conditions.

\[
S < S_{1\text{max}} = \frac{D_{\text{lim}} - 2W}{2N - 1} - W
\]

\[
S < S_{2\text{max}} = \frac{2D_{\text{lim}} - (2W + 4\bar{r}_{\text{avg}})}{2N - 1} - W
\]

Where, \( S_{1\text{max}} \) is allowable maximum coil internal spacing and \( S_{2\text{max}} \) is allowable maximum external spacing.

\[
L = \mu_0N^2\bar{r}_{\text{avg}}\left(\ln \frac{2.46}{\beta} + 0.2\beta^2\right)
\]

\[
R = R_0 + R_a
\]

\[
R_a = 320\pi^4N^2\left(\frac{\pi\bar{r}_{\text{avg}}^2}{a^2}\right)^2
\]

\[
R_0 = \left(\frac{\mu_0W}{2\sigma}\right)^{\frac{1}{2}}N\bar{r}_{\text{avg}}
\]

\[
Q = \frac{w}{R}
\]

Here,
- \( L \) - spiral coil Inductance (Henrys)
- \( R \) - equivalent resistance (Ohms)
- \( R_0 \) - ohmic resistance (Ohms)
- \( R_a \) - equivalent radiation resistance (Ohms)
- \( Q \) - quality factor,
- \( \sigma \) - conductivity of the wire,
- \( \beta \) - filling rate,
- \( a \) - radius of wire and
- \( w \) - angular frequency

When two coil are coaxially coupled, its mutual inductance is calculated by

\[
M = \frac{\mu_0\pi N_1N_2r_{1\text{avg}}^2r_{2\text{avg}}^2}{2(D^2 + r_{1\text{avg}}^2)^{1.5}}
\]

The system working parameters are given in the following table:

<table>
<thead>
<tr>
<th>V</th>
<th>f(kHz)</th>
<th>N</th>
<th>Zdist(mm)</th>
<th>P(W)</th>
<th>( \eta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>51</td>
<td>20</td>
<td>15</td>
<td>3350</td>
<td>95.5</td>
</tr>
</tbody>
</table>

Table:1 System working parameters

The equation for calculating power product is as follows.

\[
P_{\eta} = P \cdot \eta = \frac{V^2w^4M^4g_1^2}{Z_2(2Z_1Z_2+w^2M^2)^3}
\]

The turns of coils are calculated from wire diameter and overall structure, being aware of the role of inter-turn voltage and wire insulation level for air breakdown.

It is suggested in this work that coils have a square form. It should be noted that square function is highly reliant on the perimeter and only slightly depending on the loop area and wire radius. As a result, the inductance of intricate forms is sometimes well approximated by a simpler shape with the same parameters.

Grover et al. investigated a number of examples for polygons with side lengths and wire radius \( R \). Using the following formula, we can simply determine inductance.

\[
L = \frac{2\mu_0s}{\pi} \left[\ln \left(\frac{a}{s}\right) - 0.52401\right]
\]

4. EFFICIENCY AND FREQUENCY

Figure:3 shows the output or power output against the receiver's success collected from the sender of the listed documents. It should be noted that efficiency increases with higher delivery power. However, performance varies and may be achieved by the same power delivered depending on system design.

The normative SAE J 2954 was created to standardize the battery charger for electric vehicles. This document describes all aesthetic qualities, including inductance, power, minimum efficiency, compatible topology, and the validation approach. SAE J 2954 specifies four power ranges for light duty EVs are presented in table:2.

The efficiency for circular and square pad have been plotted and compared with the help of ANSYS twin builder as shown in fig.4. It is clearly seen that the square pad is having much superior efficiency than circular pad, when all other parameters were kept similar.
5. MODELLING AND SIMULATION OF PADS

Figure 5 shows how coefficient of coupling varies with vertical misalignment ranges from 5 to 200 mm between GA and VA. Magnitude of coefficient of coupling reflects flux linkage between the pads. A greater coupling values indicate stronger connection between both the power pads, which is vital for EV charging systems.

When the vertical misalignment is 5 mm between power pads, the coupling coefficient is maximum and equal to 0.683323243 & 0.834986118 for circular and square pads respectively. With increasing vertical displacement, the coupling coefficient steadily diminishes. The coupling coefficient drops to 0.045662554 and 0 for square and circular pads respectively. The values drops when distance between GA and VA increases, similar in both geometries. The coupling coefficient of square pads is greater than that of circular pads and the difference is more significant for larger misalignments.

Table 3: Misalignment and K for square & circular pad

<table>
<thead>
<tr>
<th>Misalignment [mm]</th>
<th>Square &quot;K&quot;</th>
<th>Circular &quot;K&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.834986118</td>
<td>0.683323243</td>
</tr>
<tr>
<td>25</td>
<td>0.542614255</td>
<td>0.3776</td>
</tr>
<tr>
<td>30</td>
<td>0.499370331</td>
<td>0.158663201</td>
</tr>
<tr>
<td>55</td>
<td>0.338690722</td>
<td>0.048921856</td>
</tr>
<tr>
<td>80</td>
<td>0.233786628</td>
<td>0.016316834</td>
</tr>
<tr>
<td>105</td>
<td>0.163085578</td>
<td>0.003007173</td>
</tr>
<tr>
<td>130</td>
<td>0.114945914</td>
<td>0</td>
</tr>
<tr>
<td>155</td>
<td>0.081905697</td>
<td>0</td>
</tr>
<tr>
<td>180</td>
<td>0.05897233</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>0.045662554</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4: Distance v/s self & mutual inductance

<table>
<thead>
<tr>
<th>ZDistt [mm]</th>
<th>Matrix1.L[IRX_In,ITX_In] [uH] - Ir='10A'</th>
<th>Matrix1.L[ITX_In,ITX_In] [uH] - Ir='10A'</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6.17137788</td>
<td>9.032130905</td>
</tr>
<tr>
<td>15</td>
<td>3.25674543</td>
<td>9.032101</td>
</tr>
<tr>
<td>25</td>
<td>1.86735467</td>
<td>9.03209087</td>
</tr>
<tr>
<td>30</td>
<td>1.432625206</td>
<td>9.032063973</td>
</tr>
<tr>
<td>35</td>
<td>1.112534467</td>
<td>9.032087</td>
</tr>
<tr>
<td>45</td>
<td>0.693645478</td>
<td>9.032063973</td>
</tr>
<tr>
<td>55</td>
<td>0.440771607</td>
<td>9.03361665</td>
</tr>
<tr>
<td>65</td>
<td>0.284673648</td>
<td>9.032063973</td>
</tr>
<tr>
<td>75</td>
<td>0.182435647</td>
<td>9.032063973</td>
</tr>
<tr>
<td>80</td>
<td>0.144431852</td>
<td>9.033990677</td>
</tr>
<tr>
<td>85</td>
<td>0.112345468</td>
<td>9.031700902</td>
</tr>
<tr>
<td>95</td>
<td>0.060965746</td>
<td>9.032824864</td>
</tr>
<tr>
<td>100</td>
<td>0.039512714</td>
<td>9.028852367</td>
</tr>
<tr>
<td>105</td>
<td>0.019373635</td>
<td>9.029584207</td>
</tr>
<tr>
<td>130</td>
<td>0</td>
<td>9.027948659</td>
</tr>
<tr>
<td>155</td>
<td>0</td>
<td>9.026987</td>
</tr>
<tr>
<td>180</td>
<td>0</td>
<td>9.0256748</td>
</tr>
<tr>
<td>200</td>
<td>0</td>
<td>9.0251324</td>
</tr>
</tbody>
</table>
When both vertical and horizontal misalignments have been used, the self and mutual inductance of square & circular power pads at 10 Ampere and 0 Ampere are seen in Figure:8.

Figure 7 shows flux density (B) in magnitude and in vector forms for square power pads for vertical misalignment of 30 mm. As pads are more misaligned, both magnetic field intensity and flux density decrease, and both are least at greatest misalignment (200 mm) of the research.

The simulations in this work are being done without considering shielding effect of ferrite bars. The coefficient (K) and mutual inductance (M) of square power pads demonstrate higher misalignment tolerance when compared to circular power pads.
The power of the square coil is measured by simulation of the square coil pad at various lateral misalignment. The simulation have been carried out using ANSYS twin Builder. Figure:10 shows the circuit diagram of the equivalent circuit.

Simulation of the wireless power transfer using square pad topology, using the system parameters given in table:1 has been analyzed using ANSYS Twin Builder. The power transfer from transmitter pad to receiver pad has been shown in Figure: 11. Highest power transfer 3350 Watts occurs during system frequency of 51.3KHz.

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**Figure 8** Distance v/s self and mutual inductance for square pad at 10 Ampere & 0 Ampere

**Figure 9** Flux density distribution at Zdist 55mm & plate at 20mm.

**Figure 10** ANSYS Twin Builder equivalent circuit.
6. CONCLUSIONS

A comprehensive and comparative analysis of square and circular pads for EV WPT systems has been presented in this research. 3D models for both geometries of power pads were designed using ANSYS Electronics and Twin Builder which is based on the SAE J2954 physical dimensions. For every pad, vertical misalignment between 5 mm and 200 mm has been chosen and results has been presented. Important aspects like coupling coefficient (K), mutual inductance (M), magnetic field strength (B), and magnetic flux density (h) were explored for both geometries. Modelling and results demonstrate that square power pads have a great potentiality for use in EV wireless charging systems.

REFERENCES


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