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Dimensioning and comparison of circular and double D coil geometries for inductive charging of electric vehicles

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Abstract

Wireless power transfer (WPT) today is not just limited to low power applications like smartphones or biomedical devices but has reached power levels up to 22 kW [1]. Wireless charging of electric vehicles is one of the widely researched area in the field of WPT. This paper deals with the dimensioning and comparison of inductive coils for 11 kW power transfer taking factors such as unidentical stationary and mobile coil sizes, different DC link voltages on stationary and mobile side, coupling factor and magnetic flux density into consideration.

Keywords: wireless power transfer, inductive power transfer, electric vehicle, ICNIRP

1 Introduction

Different suppliers are trying to built highly efficient, light weighted and compact inductive power transfer (IPT) system for charging of electric vehicles. IPT systems up to 7.2 kW are commercially available [7]. But the challenge still remains to charge the battery in time comparable to conductive charging with cables. This demands for the development of high power IPT systems. The WPT or IPT system exhibit benefits like spark-free charging without cables, protection against vandalism, convenient charging when parked or even in motion.
An important aspect in the development of a WPT system is the coil design. Power is transferred from transmitter to receiver coil through electromagnetic induction. The two geometries namely circular and double D were extensively simulated in COMSOL(COMSOL Multiphysics®modelling software [2]) for specific mutual inductance, different coupling factor and magnetic flux density as defined in the ICNIRP [4] standard. Here onwards, the transmitter and receiver coils are referred as stationary and mobile coils respectively.

2 System description

The technical specifications of the WPT system are presented in the table 1. In order to transfer 11 kW over a distance of 210 mm [3], we need coils that have significant self inductance. This demands higher VA rating of converter on the stationary side [5]. Therefore, compensation capacitors are used to minimize the impedance offered by the coils and enabling power transfer to the mobile side with almost unity power factor. Different compensation topologies[5] series-series, series-parallel, parallel-series and parallel-parellel exist but investigation of compensation topologies is not within the scope of this paper, here series-series compensation is considered [6].

Table 1: Technical specifications of the WPT system

Parameter	Variable	Value
Nominal Power	P_N	11 kW
Operating frequency	f_{sw}	85 kHz
Primary DC link voltage	V_{dc1}	700 V
Primary current	I_1	17.5 Arms
Secondary DC link voltage	V_{dc2}	400 V
Secondary secondary	I_2	30.5 Arms
Mechanical air gap	d_{mech}	140-210 mm

The power transfer from stationary to mobile side depends mainly on the coupling between the two coils. The coupling factor k is defined in equation (1) where L_m is the mutual inductance, L_1 and L_2 are the self inductances, $L_{\sigma 1}$ and $L_{\sigma 2}$ are the leakage inductances of stationary and mobile coils respectively.

$$k = \frac{L_m}{\sqrt{L_1 \cdot L_2}} \tag{1}$$

$$L_1 = L_{\sigma 1} + L_m \tag{2}$$

$$L_2 = L_{\sigma 2} + L_m \tag{3}$$

At resonance, the series-series compensation topology behaves as constant current source for the load [6]. The current I_2 is independent of the load and depends only on the primary voltage V_{dc1}, mutual inductance L_m and operating frequency f_{sw} as given in the equation (4).

$$I_2 = \frac{\frac{2 \cdot \sqrt{2} \cdot V_{dc1}}{\pi}}{L_m \cdot (2 \cdot \pi \cdot f_{sw})} \tag{4}$$

3 Dimensioning of the inductive coils

The secondary dc link voltage V_{dc2} is fixed in accordance to the traction battery voltage. A constant I_2 can be calculated for nomimal power transfer. Equation (4) can be rearranged to calculate the minimum mutual inductance required to induce this secondary current I_2 at constant V_{dc1}.

According to the standard for the power classes [3], unidentical sizes are chosen for stationary and mobile coils in case of both geometries. The outer dimensions are however the same for both geomteries to make them comparable. The stationary pad and mobile pad are limited to 800 x 800 mm and 400 x 400 mm respectively. The coupling factor k depends on the geometry of the coils and not on the number of turns. The parameters inner radius, outer radius for the stationary and mobile coils of the circular geometry were varied in COMSOL for the maximum coupling factor k at 210 mm vertical distance. Likewise, the parameters for the double D geometry were evaluated for maximum k. The cross-sectional sketch for both the geometries are shown in the figure 1. Overall dimensions are detailed in the table 2.

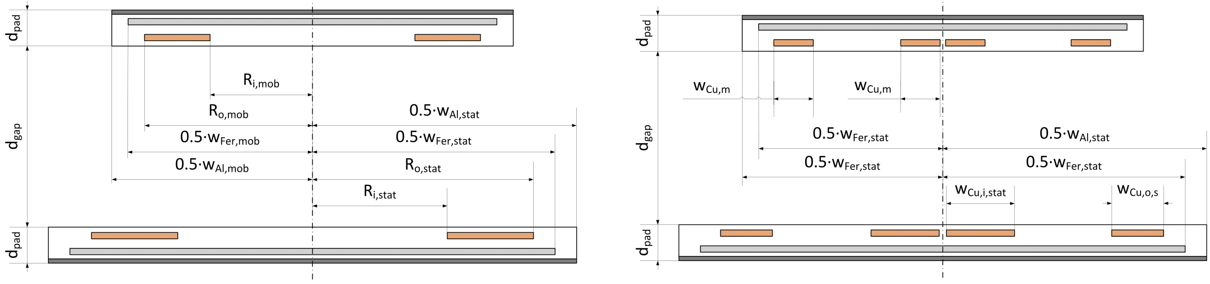


Figure 1: Cross-sectional view of the circular and double D coils

Table 2: Overall dimensions of the circular and double D coil pads

Circular coils		Double D coils	
Variable	Value(mm)	Variable	Value(mm)
$w_{Al,stat}$	800	$w_{Al,stat}$	800
$w_{Fer,stat}$	776	$w_{Fer,stat}$	776
$R_{o,stat}$	376	$w_{Cu,i,stat}$	100
$R_{i,stat}$	270	$w_{Cu,o,stat}$	90
d_{gap}	129-199	d_{gap}	129-199
$w_{Al,mob}$	400	$w_{Al,mob}$	400
$w_{Fer,mob}$	388	$w_{Fer,mob}$	388
$R_{o,mob}$	188	$w_{Cu,i,mob}$	70
$R_{i,mob}$	92	$w_{Cu,0,mob}$	70

The maximum flux density on the other hand depends on the coil geometry as well as on the number of turns. The number of turns for both geometries are calculated ensuring nominal power transfer at maximum vertical distance. The idea is to minimize the energy in stationary and mobile coils together. For the nominal power transfer, the currents I_1 and I_2 are known. The self inductance per winding A_{L1} and A_{L2} at 210 mm vertical distance for both the coils are found from COMSOL simulation. Total energy in both stationary and mobile coils is calculated by:

$$E_g(n_1, n_2) = \frac{I_1^2 \cdot L_1(n_1) + I_2^2 \cdot L_2(n_2)}{2} \tag{5}$$

$$L_1(n_1) = n_1^2 \cdot A_{L1} \tag{6}$$

$$L_2(n_2) = n_2^2 \cdot A_{L2} \tag{7}$$

Using the equation (1) the following relation between coupling factor, main inductance, the stationary number of turns n_1 and and mobile number of turns n_2 is obtained:

$$n_2(n_1) = \frac{L_m}{n_1 \cdot k \cdot \sqrt{A_{L1} \cdot A_{L2}}} \tag{8}$$

The following flowchart explains the procedure to determine the number of turns. This approach is used for both circular and double D coil geometries. The minimum energy point is found when both stationary and mobile coil energies are the same. A plot is shown in the figure 3 showing the lowest energy in case of both geometries as function of n_1.

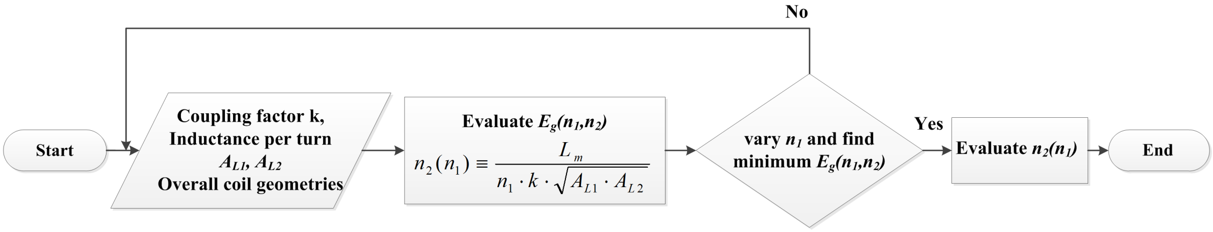


Figure 2: Flowchart to determine the number of turns of the coils

4 Simulation results

The finalized geomtery is simulated in COMSOL for coupling factor, maximum flux density with different vertical and horizontal displacement of the mobile coil. The coupling factor is shown in the figure 4 for both the coil geometries and specifications of the simulated coils are mentioned in table 3. At mininum vertical distance double D coil show better coupling factor up to 18% and with maximum vertical distance, circular geometry show high coupling factor of 12%.

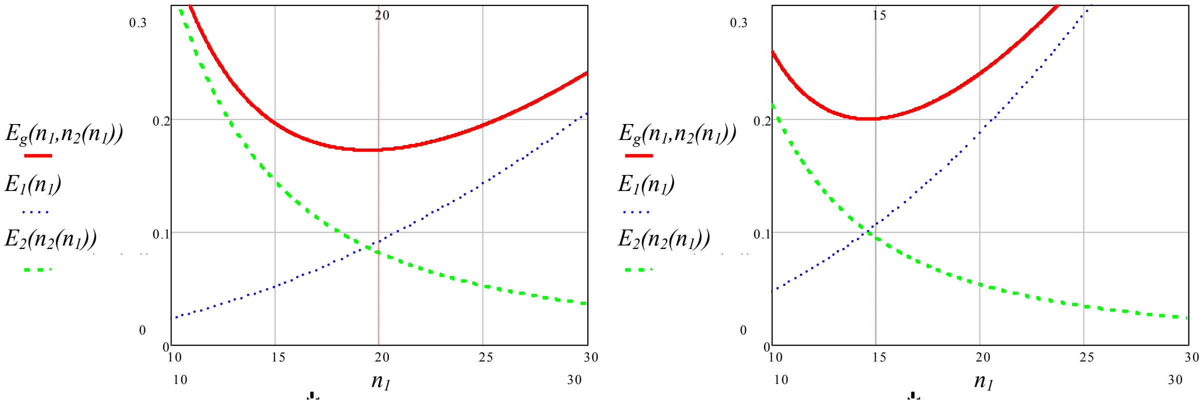


Figure 3: Energy in circular and double D coils respectively

Table 3: Technical specifications of the coils

Parameter	DD coils	Circular coils
Stationary coil turns, n_1	15	20
Mobile coil turns, n_2	15	18
Coupling factor, k	10.34 %	11.8 %
Mutual inductance, L_m	38.63 μH	38.63 μH
Self inductance (stationary), L_1	687.10 μH	597.52 μH
Self inductance (mobile), L_2	202.37 μH	181.02 μH
Leakage inductance (stationary), $L_{\sigma 1}$	648.47 μH	555.89 μH
Leakage indutance (mobile), $L_{\sigma 2}$	163.74 μH	141.39 μH

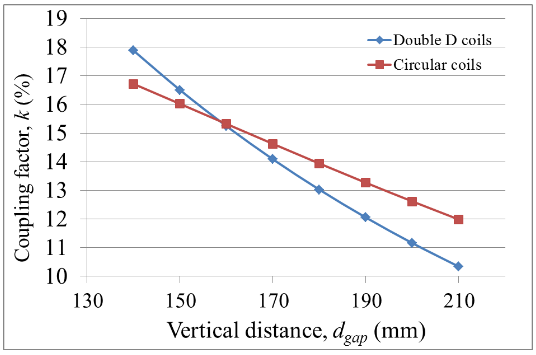
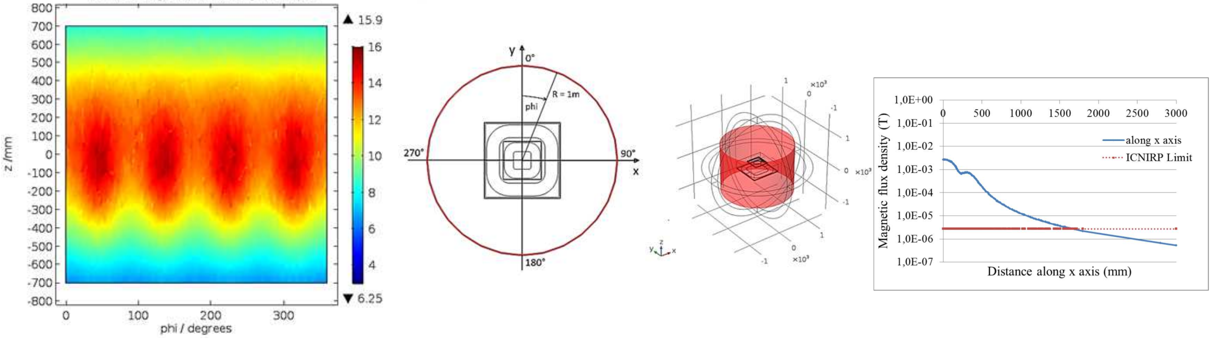


Figure 4: Coupling factor for the circular and Double D coils

The x and y mislignment (refer figure 5 b,g)of mobile coils have also been investigated. The coupling factor of double D coils decreases drastically in x direction. The car driver is more flexible in x direction as compared to y direction.

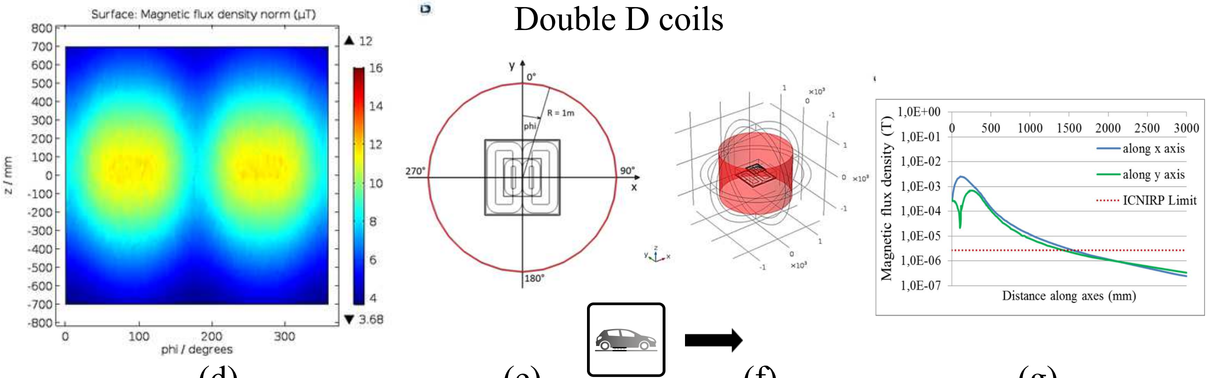
The simulated maximum flux density B, coil orientation and 3D model for both geometries are shown in the figure 5. The reference level for general public exposure of B field according to ICNIRP is 27 μT [4]. Figure 5 shows maximum flux density values up to 16 μT for circular coils and 11.5 μT for double D coils that are well within the limit.

Circular coils



(a) (b) (c) (d)

Double D coils



(d) (e) (f) (g)

Figure 5: Figure a,d show B field on cylindrical surface at 1 m. Figure b,e show orientation of coils in car. Figure c,f show 3D model simulated in COMSOL. Figure d,g show B field along x-axis and y-axis on plane middle between stationary and mobile coils.

5 Conclusion and future work

The double D coils show less magnetic field emission as compared to the circular coils. But the double D coils are more sensitive to misalignment than circular coils. Drastic misalignment could result in charging below the nominal power level. Losses in ferrite and aluminium were modelled in COMSOL. Further comparative analysis can be made considering the losses in litz wires for both geometries.

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