Performance Comparison of Inductive Charging Systems for Electric Buses

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***Abstract*— A comparative analysis of multi- coil transmitter inductive power system for electric buses is proposed in the paper. The goal of the analysis is to identify the behavior of air-core multi-coils transmitter in alignment and misalignment conditions that are often present in the considered application, comparing the results with the standard case of single coil transmitter. The analysis is carried out using analytical models for the wireless power system and finite element analysis to calculate the main electrical parameters necessary to identify the model. A case study is analyzed referring to a transmitter and a receiver with a square coil in order to evaluate the qualitative behavior of the system.**

***Keywords*— electric bus, multiple transmitters, inductive power transfer, wireless power transfer**

I. INTRODUCTION

Inductive power systems (IPS) play an important role in the electrification of mobility [1÷3]. In fact, the request to facilitate the static charging of vehicles without the use of connections or the possibility of recharging the vehicle during the motion are contributing to the development of numerous IPS architectures [4]. These systems can also play a very important role in electrification of urban areas, especially to manage the fleets of electric buses [5]. In fact, many papers have analyzed the advantages and proposed new solutions for the integration of wireless power recharge for electric buses [6÷9]. Considering the architecture of a bus, it is easy to notice the availability of a large surface on the chassis, that can be used for wireless power exchange. In practical applications, one of the disadvantages is due to the misalignment that occurs during the bus operations and related to the error of the driver or to the presence of obstacles along the transmitter pad. Another important aspect of the IPT is related to the necessity to guarantee a high level of reliability [10,11]. Therefore, a solution of multi-coils transmitter pad instead of the common single coil pad could be interesting. Many papers analyze the use of multi-coils IPS, evaluating the effects of the multiple coils [12÷14] or the magnetic flux density distribution to improve the performance [15].

The goal of this paper is inherent the study of the behavior of a multi-coil transmitter pad used for electric buses, with a focus on the efficiency and mutual coupling with and without misalignment, with the aim to establish further advantages in the use of multi-coils configurations. The analysis is performed by means of analytical models able to describe the IPS operating conditions, while the finite element analysis is adopted to calculate the electrical parameters used in the analytical models.

II. MULTI-COILS ARRANGMENTS FOR IPT

The use of inductive power systems for electric buses has a lot of advantages, such as the possibility of recharging the vehicle during its short and numerous stops. Furthermore, the dimensions of the bus ensure a large available surface along the chassis of the vehicle which allows for quite significant exchange powers to be obtained during the recharging phase. Even though the charging surface for the IPT system is large, misalignment between the transmitting and receiving pads may occur often, with consequent reduction of the IPT system performance. This misalignment can assume significant values especially if the road surface related to the stops is partially unusable. Therefore, the use of pads made up of multi-coil can be useful and such configurations are analyzed in this paper. In the following, the mathematical models of single and multi-coil IPS are reported.

A. Case of transmitter pad with a single coil and receiver pad with single coil

The traditional configuration of an IPT system is composed of a single coil transmitter pad and a single coil receiver pad, as shown in fig.1.

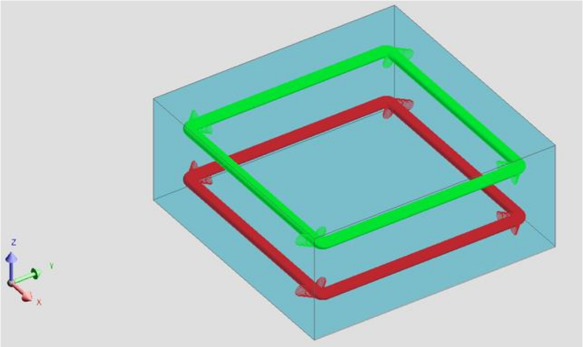


Fig.1 Single coil transmitter and receiver pad configuration.

Considering a series compensated circuit for both the receiver and transmitter, the electrical circuit that describes the system is shown in fig.2.

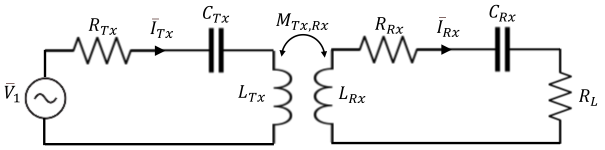


Fig.2 Electrical circuit for the case of one coil for the transmitter and receiver pad.

The two coils are mutually coupled by the coefficient $M_{Tx,Rx}$, while the self-inductances are compensated by the series capacitors C_{Tx} and C_{Rx}, so that the impedances $z_{Rx} = j\omega L_{Rx} + 1/(j\omega C_{Rx})$ and $z_{Tx} = j\omega L_{Tx} + 1/(j\omega C_{Tx})$ are zero. With these assumptions, the mathematical model of the system is expressed by:

$$\begin{bmatrix} \bar{V}_1 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{Tx} & -j\omega M_{Tx,Rx} \\ j\omega M_{Rx,Tx} & -(R_{Rx} + R_L) \end{bmatrix} \begin{bmatrix} \bar{I}_{Tx} \\ \bar{I}_{Rx} \end{bmatrix} \qquad (1)$$

In (1), ω is the resonance frequency of the system and R_L is the load that is fed by the receiver pad. In this case, it is easy to determine also the efficiency of the transmission, that is defined as:

$$\eta = \frac{R_L I_{Rx}^2}{\mathrm{Re}\{\bar{V}_1\, \bar{I}_{Tx}^*\}} \qquad (2)$$

Using equation (1), the efficiency (2) of wireless power transfer can be evaluated as:

$$\eta = \frac{R_L \left(\omega M_{Tx,Rx}\right)^2}{(R_{Rx} + R_L)\left[R_{Tx}(R_{Rx} + R_L) + \left(\omega M_{Tx,Rx}\right)^2\right]} \qquad (3)$$

B. *Case of transmitter pad with four coils and receiver pad with single coil*

Fig.3 shows the configuration where the transmitter pad is divided into four independent coils, while the receiver pad is still composed by a single coil.

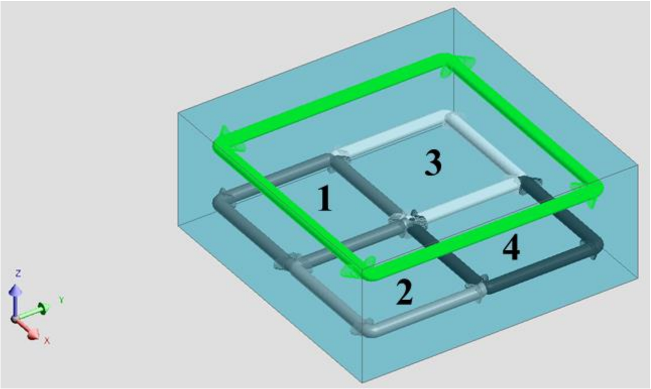


Fig.3 Single coil receiver and four coils transmitter configuration.

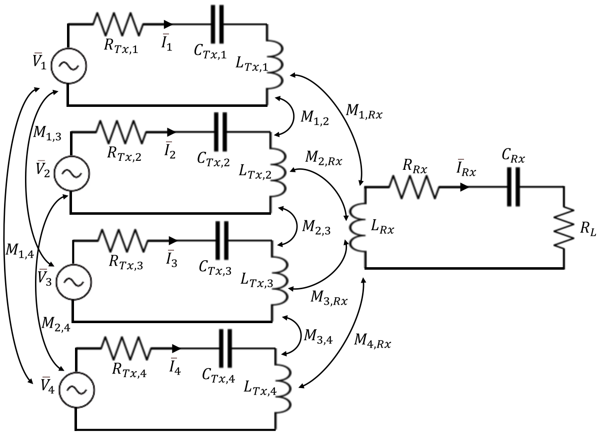


Fig.4 Electrical circuit for the case of four coils for the transmitter and one coil for the receiver pad.

As reported in fig.4, all the transmitter coils are magnetically coupled with the receiver one by four different mutual coefficients $M_{1,Tx}$, $M_{2,Tx}$, $M_{3,Tx}$ and $M_{4,Tx}$, and with each transmitter coils by the mutual inductances $M_{h,k}$, (with the h and k indexes variable from 1 to 4, $h \neq k$ and $M_{h,k} = M_{k,h}$).

Using a series compensation for the primary and secondary coils, the electrical model is:

$$\begin{bmatrix} \overline{V}_1 \\ \overline{V}_2 \\ \overline{V}_3 \\ \overline{V}_4 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{Tx,1} & -j\omega M_{1,2} & -j\omega M_{1,3} & -j\omega M_{1,4} & -j\omega M_{1,Rx} \\ -j\omega M_{1,2} & R_{Tx,2} & -j\omega M_{2,3} & -j\omega M_{2,4} & -j\omega M_{2,Rx} \\ -j\omega M_{1,3} & -j\omega M_{2,3} & R_{Tx,3} & -j\omega M_{3,4} & -j\omega M_{3,Rx} \\ -j\omega M_{1,4} & -j\omega M_{2,4} & -j\omega M_{3,4} & R_{Tx,4} & -j\omega M_{4,Rx} \\ j\omega M_{1,Rx} & j\omega M_{2,Rx} & j\omega M_{3,Rx} & j\omega M_{4,Rx} & -(R_{Rx} + R_L) \end{bmatrix} \begin{bmatrix} \overline{I}_1 \\ \overline{I}_2 \\ \overline{I}_3 \\ \overline{I}_4 \\ \overline{I}_{Rx} \end{bmatrix} \qquad (4)$$

And the efficiency is calculated as:

$$\eta = \frac{R_L I_{Rx}^2}{\mathrm{Re}\{\overline{V}_1\, \overline{I}_1^*\} + \mathrm{Re}\{\overline{V}_2\, \overline{I}_2^*\} + \mathrm{Re}\{\overline{V}_3\, \overline{I}_3^*\} + \mathrm{Re}\{\overline{V}_4\, \overline{I}_4^*\}} \qquad (5)$$

Equation (5) is not easily modified in the same manner as (3), therefore the evaluation of (5) will be made in numerical manner.

C. Case of transmitter pad with eight coils and receiver pad with single coil

The last examined configuration is shown in fig. 5, with the electrical model in fig. 6.

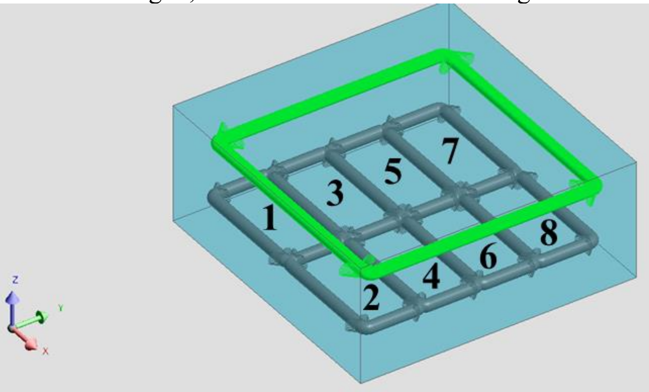


Fig.5 Electrical circuit for the case of eight coils for the transmitter and one coil for the receiver pad.

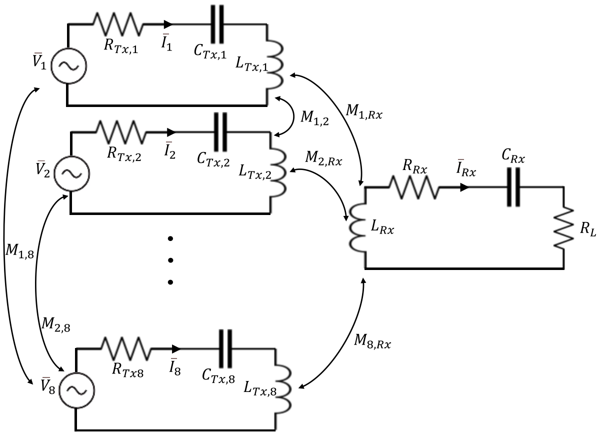


Fig.6 Electrical circuit for the case of eight coils for the transmitter and one coil for the receiver pad.

The electrical model and the efficiency are expressed by equations (6) and (7). With eight transmitter coils pads, the complexity of the model and of the magnetic analysis increases, due to the necessity to identify more mutual coefficients among the transmitter coils and among them and the receiver one.

$$\begin{bmatrix} \bar{V}_1 \\ \bar{V}_2 \\ \vdots \\ \bar{V}_8 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{Tx,1} & -j\omega M_{1,2} & \cdots & -j\omega M_{1,8} & -j\omega M_{1,Rx} \\ -j\omega M_{1,2} & R_{Tx,2} & \cdots & -j\omega M_{2,4} & -j\omega M_{2,Rx} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ -j\omega M_{1,4} & -j\omega M_{2,4} & \cdots & R_{Tx,4} & -j\omega M_{4,Rx} \\ j\omega M_{1,Rx} & j\omega M_{2,Rx} & \cdots & j\omega M_{4,Rx} & -(R_{Rx}+R_L) \end{bmatrix} \begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \\ \vdots \\ \bar{I}_8 \\ \bar{I}_{Rx} \end{bmatrix} \qquad (6)$$

$$\eta = \frac{R_L I_{Rx}^2}{\sum_{m=1}^{8} \mathrm{Re}\{\bar{V}_m \, \bar{I}_m^*\}} \qquad (7)$$

III. NUMERICAL SIMULATIONS

The numerical simulations proposed in the paper are carried out considering an IPS composed of two pads and with the geometrical data reported in Table I. For the case with 4 and 8 coils for the transmitter pad, the sizes of the receiver pad are divided in uniform sub-coils.

TABLE I. MAIN DATA OF THE IPT SYSTEM

Shape of the pad	Rectangular
Sizes	0.4 m x 0.4 m
Number of turns	1
Diameter of the conductor	10 mm
Frequency	85 kHz
Resistance of coils at 85 kHz	2.4 mΩ

Using a 3D finite element analysis carried out with the software Flux Altair, the self-inductances and the mutual inductances for the above considered cases are calculated and reported in Tables II÷IV, assuming the correct alignment between the receiver and the transmitter pads.

TABLE II. SELF AND MUTUAL INDUCTANCES FOR THE CASE IN PARAGRAPH II.A

L_{Rx}	1.05 μH
L_{Tx}	1.05 μH
$M_{Tx,Rx}$	0.275 μH

TABLE III. SELF AND MUTUAL INDUCTANCES FOR THE CASE IN PARAGRAPH II.B

L_{Rx}	1.05 μH
$L_{Tx,1}$, $L_{Tx,2}$, $L_{Tx,3}$, $L_{Tx,4}$	0.410 μH
$M_{1,Rx}$, $M_{2,Rx}$, $M_{3,Rx}$, $M_{4,Rx}$	0.068 μH
$M_{1,2}$	0.068 μH
$M_{1,3}$	0.015 μH
$M_{1,4}$	0.068 μH
$M_{2,3}$	0.068 μH
$M_{2,4}$	0.015 μH
$M_{3,4}$	0.068 μH

TABLE IV. SELF AND MUTUAL INDUCTANCES FOR THE CASE IN PARAGRAPH II.C

L_{Rx}	1.05 μH
$L_{Tx,1}$, … , $L_{Tx,8}$	0.26 μH
$M_{1,Rx}$, $M_{2,Rx}$, $M_{7,Rx}$, $M_{8,Rx}$	0.030 μH
$M_{3,Rx}$, $M_{4,Rx}$, $M_{5,Rx}$, $M_{6,Rx}$	0.038 μH
$M_{1,2}$, $M_{3,4}$, $M_{5,6}$, $M_{7,8}$	0.025 μH

$M_{1,3}$, $M_{3,5}$, $M_{5,7}$	0.057 μH
$M_{2,4}$, $M_{4,6}$, $M_{6,8}$	0.057 μH
$M_{1,4}$, $M_{3,6}$, $M_{5,8}$	9.39 nH
$M_{2,3}$, $M_{4,5}$, $M_{6,7}$	9.39 nH
$M_{1,5}$, $M_{2,6}$, $M_{3,7}$, $M_{4,8}$	5.17 nH
$M_{1,6}$, $M_{2,5}$, $M_{3,8}$, $M_{4,7}$	2.24 nH
$M_{1,8}$, $M_{2,7}$	0.91 nH
$M_{1,7}$, $M_{2,8}$	1.47 nH

The obtained values of inductances are used in equations (1), (4) and (6). The solutions of the equations give the possibility to evaluate the quality of the coupling between the receiver and the transmitter pads and calculate the efficiency of the three configurations. In order to of carrying out a purely qualitative analysis, the calculations are made by imposing that the supply voltage of each transmitter coil is equal to 1 V (as rms value). Fig. 7 shows the coupling coefficient between the receiver and the transmitter for the different configurations examined. In the case of eight transmitter coils, there are two coupling coefficients because the mutual inductance of the inner coils is slightly different than the mutual inductance of outer coils (e.g., $M_{1,Rx}$ and $M_{3,Rx}$ reported in table IV). The analysis obviously highlights a reduction of the coupling coefficients between the case of a single coils and a multi-coils configuration, but the reduction is not proportional to the number of coils adopted.

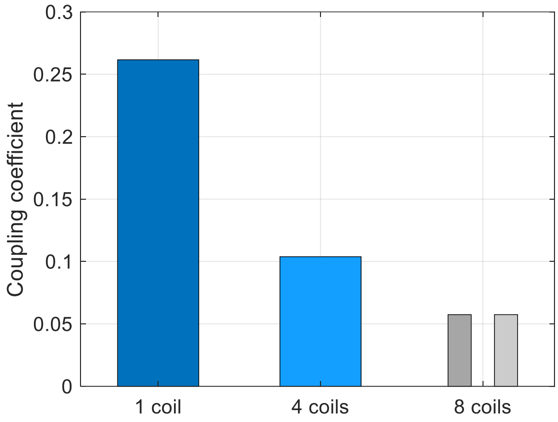


Fig.7 Coupling coefficient for the three configurations, without misalignment between receiver and transmitter.

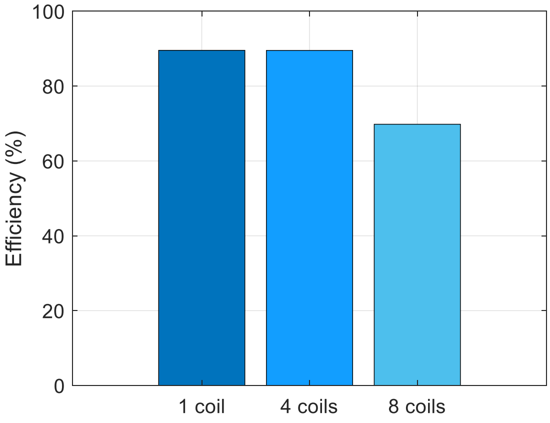


Fig.8 Efficiency evaluated for the three configurations, without misalignment between receiver and transmitter.

This aspect could be important for the misalignment between the pads and the results will be reported in the following paragraph. Regarding the efficiency reported in fig.8, the reduction is very small for the case of 4 coils, while it becomes more evident for the case of 8 coils on the transmitter.

A. Misalignment effects on the behavior of multicoils pad

The effects of misalignment on the mutual inductance between the transmitter and receiver coils are reported in figs. 9, 10 and 11, while the variations of efficiency and coupling coefficients are shown in figs. 12 and 13.

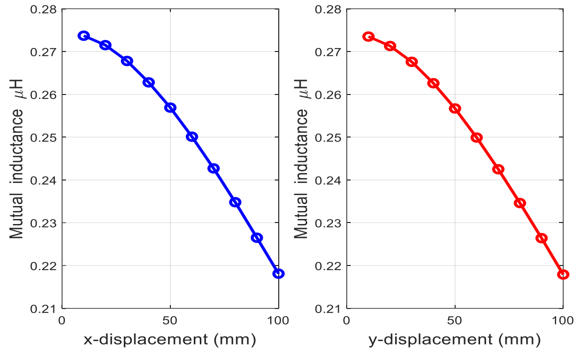


Fig.9 Mutual inductance variation versus x and y displacement for the case of single pad for the transmitter coil.

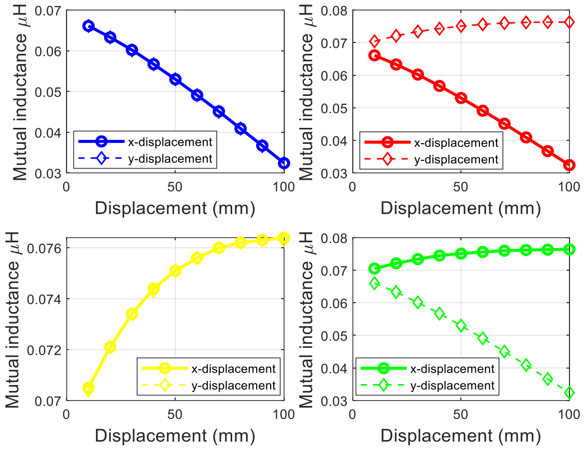
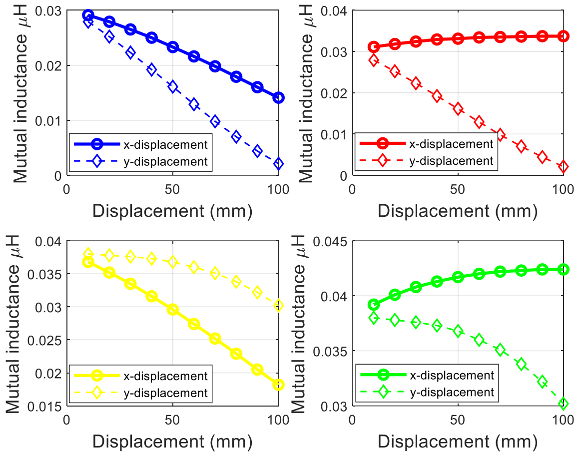


Fig.10 Mutual inductance variation versus x and y displacement for the case of four pads for the transmitter coil: variation respect the four different pads (the x displacement is with continuous line; the y displacement with the dashed line).



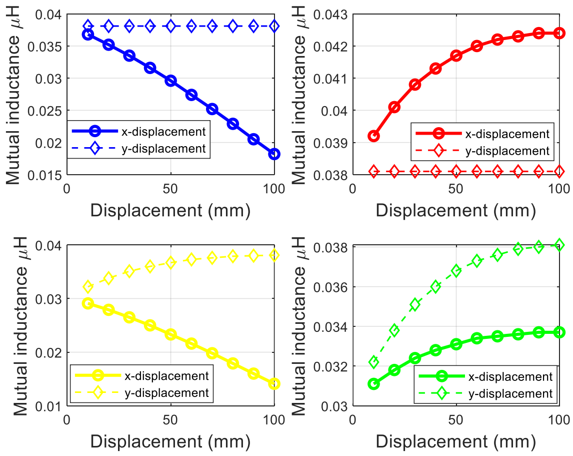


Fig.11 Mutual inductance variation versus x and y displacement for the case of eight pads transmitter coil: variation respect the eight different pads (the x displacement is with continuous line; the y displacement with dashed line).

The misalignment analysis is carried out by considering two different variations along the x-axis and the y-axis of the receiver coil. Both variations are between 2.5% and 25% of the pad sizes along x and y. The square geometry adopted for the coils determines the same variation of mutual inductance along the x and y axes for the case of transmitter composed by a single pad, fig.9. The reduction of the mutual inductance is above 1% from the first displacement point and reaches 20% in the final position with respect to the values in aligned condition. Quite different is the behavior of the mutual inductance for the cases of 4 pads and 8 pads for the transmitter coil. In fact, in these cases the different position of the pads determines the reduction or the slight increase of the mutual inductance. In the case of Fig.10, the direction of the movement along the x-axis increases the mutual inductance in pads 3 and 4, which are overlapped by the receiver coils; the same behavior is obtained along the misalignment on the y-axis, where the two pads involved in the increase of mutual inductances are 2 and 4. Obviously, the change in misalignment direction also determines a modification of the pads involved, but the qualitative behaviors of the mutual inductance variations are the same. Similar considerations can be made for the case of eight pads for the transmitter coils, reported in fig. 11. The efficiency variations during the misalignment along x- and y- direction are below 10 % for the case of one or four coils for the transmitter; instead, the case of 8 coils is characterized by a reduction along the x- axis movement and a slight increase followed by a reduction for the misalignment along y-axis, fig.12. These behaviors are confirmed with the coupling coefficients reported in fig.13. It is evident that for the case of 8 coils the misalignment along the y-axis determines a slight increase of coupling coefficient for some coils, with positive effects on the efficiency.

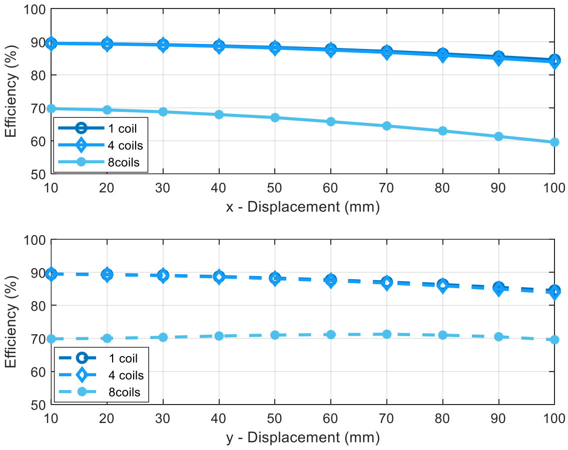


Fig.12 Efficiency variation versus x and y displacement, for the case of 1 pad, 4 pads and 8 pads for the transmitter coil.

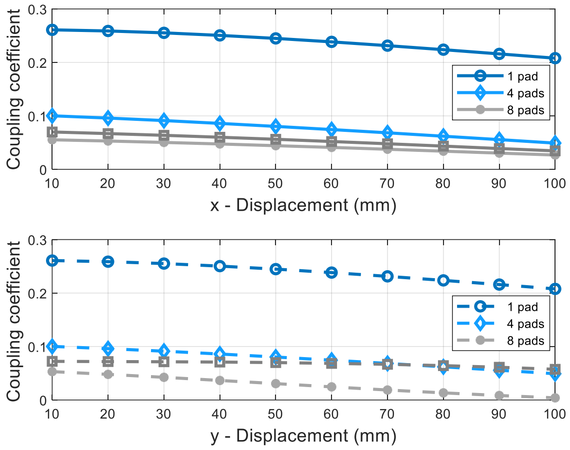


Fig.13 Coupling coefficient variation versus x and y displacement, for the case of 1 pad, 4 pads and 8 pads for the transmitter coil.

IV. CONCLUSIONS

The paper proposes an analysis of different pad configurations for the IPT systems used for electric buses. The main idea of the paper is to analyze the use of parallel multi-coil configurations for the transmitter pad, with the aim to increase the system reliability and analyze the performance in the misalignment conditions. A numerical investigation is carried out using finite element analysis and considering a square coil as a case study. The results reported in the paper demonstrate the convenience of using single coils transmitter and receiver pads, that allows the possibility to obtain the higher values of efficiency and coupling coefficient, both with the perfect alignment and in misalignment conditions. On the contrary, the single coils configuration is not convenient from a reliability point of view: in fact, a fault on the transmitter coil electrical drives determines the out of order of the entire system, but this is not verified for the case of multi-coils transmitter pads.

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