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Method for Calculating Coupling Coefficients in Dynamic Energy Transfer for Electric Vehicles

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***Abstract*—Optimizing the efficiency of primary and secondary coil configurations for Dynamic Wireless Power Transfer (DWPT) in Electric Vehicles (EVs) requires means for accurate calculation of the mutual inductance in an array of coils. Based on finite element simulation method, we present a quick and accurate method for calculating the energy transfer capabilities of a given DWPT array. By consecutively switching on and off every coil and driving them with a constant current ramp rate, mutual inductances and a coupling coefficient matrix of the whole configuration is easily calculated. This method allows for relatively easy optimization and up-scaling of DWPT systems to multiple arrays of primary and secondary coils as well as implementing various coil designs and configurations. The data acquired using this method may also be used during real-time applications providing indications of vehicle relative alignment.**

I. Introduction

As electric vehicles (EVs) are becoming more popular, several technologies are competing to make their imprint in the market. Each EV technology has its advantages and disadvantages that may promote their use for different applications, optimizing their efficiency.

A comprehensive assessment of modern inductive power transfer systems for transportation may be found in [1].

ElectRoad Ltd. [2] is one of the few firms that are working on developing a system based on Dynamic Wireless Power Transfer (DWPT) [3].

The DWPT technology is predominantly dependent on the magnetic coupling achieved between primary transmitting coils within the road, and secondary coils situated under the vehicle chassis.

This makes optimization of the coupling between the coils a decisive factor in the efficiency of the technology and its ultimate success in implementation.

It is the purpose of this article to introduce a method that allows simulating the coupling coefficients between multiple arrays of coils, regardless of their topology, yielding the essential information needed to determine the design's power transfer capabilities.

The method also takes into consideration the exact location of the coils and effects of other structures/materials in the vicinity.

I. Current Technological Challenges

Although it seems that technology is in a fast-moving direction towards achieving efficient, game-changing EVs, there are still several problems that must be solved.

These include:

- Ensuring electrical safety in handling high power lines, especially in extreme weather
- Increasing the speed of recharging
- Decreasing the EV system's weight

Wireless energy transfer is an emerging technology that presents a solution to these problems [1], [4] and [5].

The DWPT solution is well based and is presented as one of the most promising technologies for EV solutions [6].

However, in order for this technology to be adopted, the optimization process needs to overcome cost and efficiency challenges.

Several methods for calculating optimization parameters for DWPT systems have been proposed [7] and [8], focusing mainly on the calculation of the magnetic flux density, where the coils are chosen with common geometrical topologies in order to ease the analysis [9].

We propose to focus on the coupling parameter between the primary and secondary coils, while also being able to calculate the self-inductance of each coil with relative ease, unreliant on using common geometrical coil topologies.

It is apparent that the coupling of the coils is not the sole parameter optimized to achieve a cost efficient product.

However, using this parameter and applying the simple method of calculation we describe below, more complex and innovative designs can be tested with ease to determine the efficiency of the coupling factors and allow for a relatively quick and simple optimization process.

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II. Mutual Inductance and Coupling Coefficients

Mutual inductance between two coils is defined by equation (1):

$$L_{2,1} = V_2 / \frac{di_1}{dt} \qquad (1)$$

where V_2 is the induced voltage on the secondary coil due to the change in current i_1 in the primary coil.

Note that the equation (1) is independent of any spatial constrictions and considers the flux leakage that can be caused by various system configurations.

The amount of mutual inductance between coupled coils is expressed as a fractional number between zero (no mutual inductance/loosely coupled) and 1 (maximum mutual inductance/tight coupling).

This parameter for two coils is given as:

$$K_{2,1} = \frac{L_{2,1}}{\sqrt{L_{1,1} \cdot L_{2,2}}} \qquad (2)$$

where $L_{1,1}$ and $L_{2,2}$ are the coils' self-inductance.

In an array of multiple coils, we can calculate all the coupling coefficients between each coil as:

$$\hat{K} = \sum_{i=1}^{N} \sum_{i=1}^{N} \frac{L_{i,j}}{\sqrt{L_{j,j^{Li,i}}}} \qquad (3)$$

where N is the sum of the number of coils in the total system (primary and secondary combined).

Thus, from a matrix representation of L (calculated or measured) we get a symmetrical matrix of the coupling coefficients where the main diagonal $K_{i,i}$ (self-coupling parameter) equals 1.

$$\begin{pmatrix} L_{1,1} & \cdots & L_{N,1} \\ \vdots & \ddots & \vdots \\ L_{1,N} & \cdots & L_{N,N} \end{pmatrix} \rightarrow \begin{pmatrix} K_{1,1} & \cdots & K_{N,1} \\ \vdots & \ddots & \vdots \\ K_{1,N} & \cdots & K_{N,N} \end{pmatrix} \qquad (4)$$

III. Simulation Method

A specific DWPT design may consist of a complex array of transmitting and receiving coils, metallic components and shields, and magnetic flux concentrators and diverters.

An example of such a possible design is shown in figure 1.

The figure displays an array of 12 transmission coils (orange), which represents a short section from a long underground transmission track. The receiving coils array (light blue in the figure 1), is embedded in the EV's chassis above the transmitting track.

The array of secondary coils in the figure is composed of 9 coils at different height levels. Also shown here is a ferrite plate mounted above the receiving array.

Each receiving coil captures a portion of the magnetic flux generated by the primary coils below. The supporting electronics integrate the induced voltage in the receiving array to maximize energy transfer.

Figure 2 displays the magnetic layout of such a design along with the magnetic field lines obtained when only the center coil in figure 2 is excited.

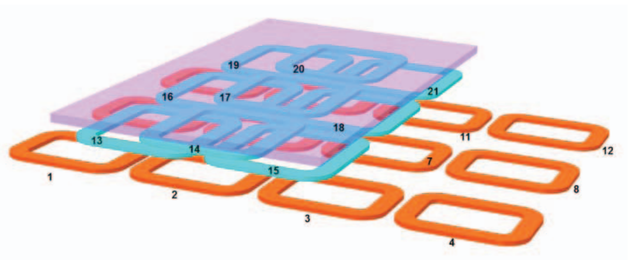

Figure 1. FEM model as simulated. Includes 12 primary coils below (orange), 9 interlapping secondary coils above (light blue) and a ferrite plate on top.

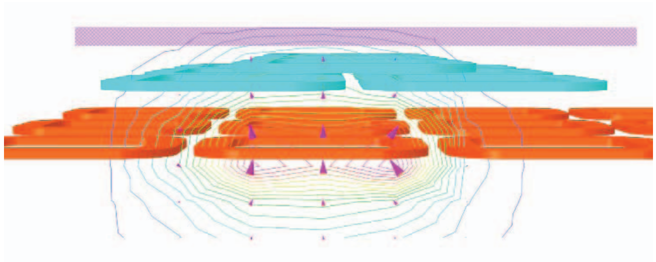

Figure 2. Magnetic Field lines as simulated within the wireless power transfer structure. Top coils are to be embedded in chassis with ferrite plate above, while bottom coils are embedded in the road.

In order to calculate the inductance matrix of such an array, finite element method simulation software, COBHAM OPERA was used.

To simplify the simulation process, the calculation of the induced voltage in the receiving coils and the transformation to the inductance matrix of the entire array, we have used a linear current ramp in every coil and recorded the induced voltage in all other coils.

A constant d_{in}/dt is fed to each coil consecutively while switching on and off the other coil circuits. A schematic example for each coil switching circuit is displayed in figure 3.

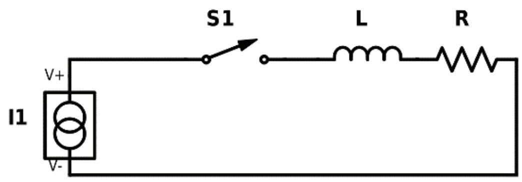

Figure 3. Simulated electrical circuit for each coil.

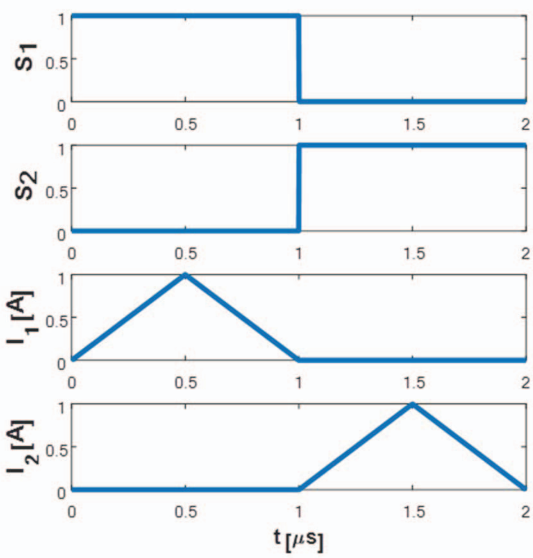

Figure 4. Switch Data Logic compared with current sources during simulation in two circuits. Each circuit has a time step to calculate the self-inductance $N_{n,n}$ and the coupling inductance $L_{n,m}$.

Figure 4 demonstrates the principle of coil switching in the simulation. Only two coils are presented here but the coil which is switched off represents all coils except for the excited one. In this example, S1 is first switched on for a period of 1 µsec during which the current is linearly ramped up to a value of 1 A and back down to zero.

During this time S_2 (and all other switches) are in the off position, preventing current flow in the associated coils. Voltage is measured on every coil in the "off" state and the mutual inductance is then calculated for each pair of coils. For the $L_{N,N}$ matrix, N^2 simulation steps are required. After the inductance matrix is calculated, a simple numerical analysis is needed to compute the $\widehat{K}$ coupling coefficients for every coil in the system as presented in figure 5.

The top left square in white presents primary windings 1-12, where the bottom and right are secondary windings 13-21.

Coefficients are calculated for the configuration as presented in figure 1 (Cross-diagonal represents $K_{i,\,i} = 1$ but is set to zero to allow proper viewing of the scaling).

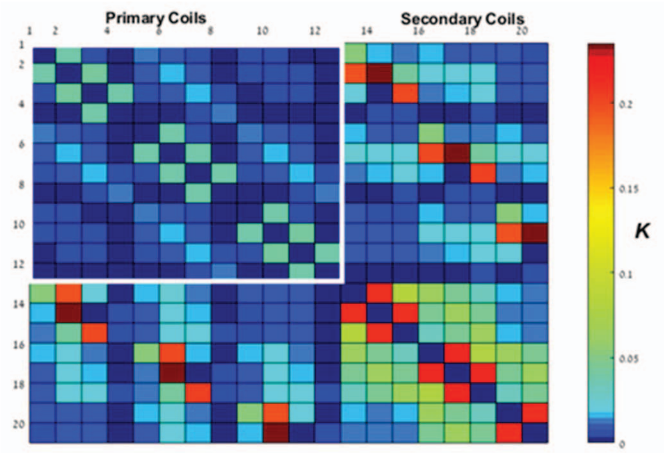

Figure 5. Coupling coefficients are presented with a colormap scale. Cross-diagonal value is set to zero to allow proper viewing of the scaling

Clearly, the coupling coefficient matrix of figure 5 is position dependent. As the secondary receiving coils pass over the transmission track, the matrix changes according to the momentary coil coupling. The matrix of figure 5 is, therefore, a snapshot of the specific state described in figure 1 and figure 2.

Here, the secondary coils 14, 17 and 20 are situated just above primary coils 2, 6 and 10 respectively. Therefore, the coefficient matrix shows maximum coupling exactly for these pairs of coils.

In the specific application where importance is placed on dynamic coupling coefficients due to the vehicle motion, multiple simulations can provide the coupling information to determine the desired switching of the primary coils to be the most power efficient.

Such analysis could make use of the most strongly coupled coils rather than the whole array which consists of a broad range of coupling coefficients.

Figures 6 - 9 show the results of displacements in the vehicle alignments.

Figures 6 - 7 model the expected motion of the vehicle as it approaches a new set of primary coils, while figures 8 - 9 present a misalignment of the vehicle traveling off of the primary coil's main axis.

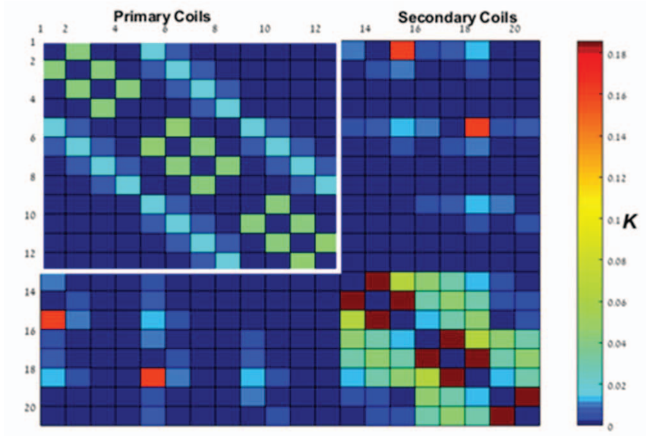

Figure 6. Coupling coefficients are presented with a colormap scale during vehicle approach (60 cm before maximum coupling matching).

Figure 7. Coil configuration for displacement of an approaching vehicle (same as in figure 6).

Through these figures is it easy to visualize the advantage of using a system of multiple arrays of primary and secondary coils.

As the vehicle approaches/leaves an array segment, the previously strongly coupled coils #14 and #2 show a decrease in there coupling factors and have been replaced in magnitude in figure 6 with #15 and #1 respectively.

A sensory device for vehicle alignment would be able to consecutively switch to transferring the power primarily through the most strongly coupled coils, thus providing a more efficient power transfer system with less radiative losses.

The method of sensing vehicle alignment may be done as well by constantly measuring the coupling coefficients and alerting the vehicle of the proper corrections to be made.

Constant measurement of the coefficients can be very straightforward when using the already known waveforms and frequencies used for the wireless power transfer, these values substituted in equations (1) and (2) produce the desired $\widehat{K}$ parameters.

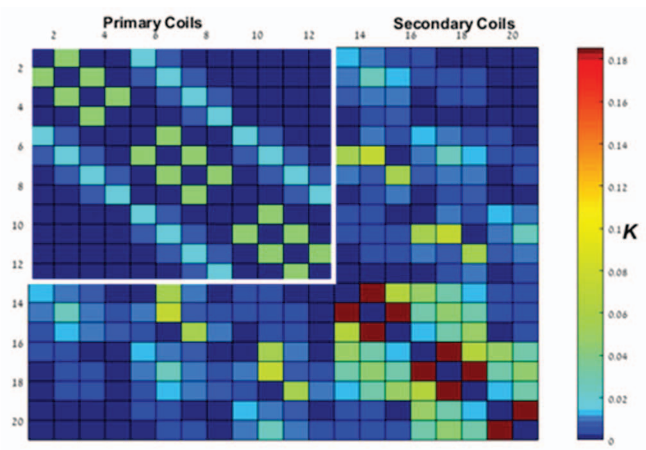

Figure 8. Coupling coefficients are presented with a colormap scale during vehicle misalignment (20 cm off of maximum coupling matching axis).

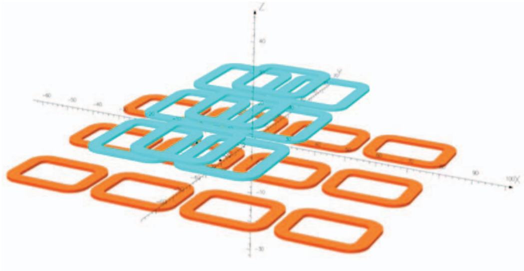

Figure 9. Coil configuration for misalignment of the vehicle (same as in figure 8).

Figures 8-9 demonstrate the case of a misaligned vehicle moving at a distance of 20 cm from the center of the primary array (similar to not driving exactly in the middle of a lane). This may be considered a common event, either while switching lanes or due to other driver activity.

This case provides an example when the coupling between two neighboring secondary or primary coils far outdoes the coupling strength between any set of secondary and primary coils. In figure 8 this is shown by consecutive coils #13 and #14 having a high coupling value compared to other pairs.

As this study presents, this coupling factor is in direct relation to the energy transfer between coils, therefore any undesired coupling between coils may lead to a loss in efficiency or other problems in the application's performance.

This analysis shows the capabilities of identifying the exact points when events like these may occur and will provide valuable information to limit undesired results.

Several solutions may be optimizing the sizes and distanced between consecutive coils to achieve the desired results.

IV. Conclusions

In this paper, various examples were presented to prove the method of concept for the analysis of wireless power transfer configurations with relative ease and short simulation times.

The goal in mind is to enhance the process needed to come up with new and better topologies and allow relatively easy optimization and up-scaling the system to multiple arrays of primary and secondary coils.

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