第 50 卷第 S1 期
2022 年 12 月

同济大学学报(自然科学版)
JOURNAL OF TONGJI UNIVERSITY(NATURAL SCIENCE)

Vol. 50 No. S1
Dec. 2022

文章编号：0253-374X(2022)S1-0165-05 **DOI：**10.11908/j.issn.0253-374x.23721

基于电阻器耦合的电动汽车感应充电定位

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摘要：目前，市场上出现越来越多的以电池为动力的电动汽车，其中大多数电动汽车必须通过有线充电装置进行充电。与之相对应的感应式无线充电系统，可以让充电过程更加舒适。无线充电系统一般由初级线圈和次级线圈组成，其中初级线圈可以建立在停车场，将电能转化为场能；次级线圈安装在车辆中，接收初级线圈能量并转化为电能，为车辆电池充电。为保证充电过程安全有效，初级线圈和次级线圈必须充分耦合，这可通过将车辆准确定位在初级线圈上方来实现。本文提出了一种简单而经济的方法来验证线圈之间的耦合是否足以满足充电条件。通过安装在次级线圈侧的电阻，来模拟在确定工作条件下无线充电系统的电池负载；电阻两端电压可以用来估计线圈之间的耦合度，以反映车辆与初级线圈的相对位置。本文在数学和物理原理的基础上解释了这个概念，并在一个真实的无线电传输线路上进行了试验评估。

关键词：电动汽车；无线动力充电；联轴器；定位

中图分类号：U469.7 **文献标志码：**A

Verification of the Positioning of Battery Electric Vehicles over an Inductive Charger, by Estimating the Coupling Through a Resistor

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Abstract：Battery-powered electric vehicles have arrived on the streets. Most electric vehicles have to be recharged by plugging-in a cable. A wireless charging system with induction makes the process more comfortable. The primary coil，build in the parking lot，transforms the electric energy into field energy. The secondary coil，build in the vehicle，receives the energy and transforms it into electric energy and recharges the battery. To ensure safe and efficient charging，the coil pair must be coupled sufficient. This is done by positioning the vehicle well enough over the primary coil.This paper presents a simple and cost-effective way to verify whether the coupling between the coil pair is sufficient enough for charging. A resistor，on the secondary side，simulates the load of the battery on the wireless charging system in defined operating condition. The voltage across the resistor can be used to estimate the coupling between the coils. This relates to the positioning of the vehicle. The paper explains the concept on the basis of mathematical and physical principles. The results are evaluated on a real wireless power transmission track.

Key words：electric vehicles；wireless power charging；coupling；positioning

The range of electric vehicles has been massively increased in recent years. Nevertheless，for everyday use vehicles must be recharged frequently. In conventional electric vehicles，this is done by connecting the vehicle to a charging point with a cable. Since the installed charging power in private parking lots is often low，the vehicles must be connected to the charging point every day. Inductive charging systems can make a relief. Here，the vehicles are recharged by electromagnetic field energy. The transmission medium is air. This means that no cable has to be connected to the vehicle to recharge it. The electric energy is transformed into an electric field energy by the primary coil. The secondary coil，build inside of the vehicle，will receive the field energy and convert it back to electric energy. For this to happen，the coils have to be coupled. This is done by positioning the vehicle，with the secondary coil，well enough over the primary

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收稿日期:2022-08-15

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coil. To make the wireless charging safe and efficient, it has to be ensured, that the coupling is sufficient enough.

In this paper a simple and inexpensive method is introduced to estimate the coupling between the coil pair. The method is easy to automate and uses the already existing infrastructure inside the vehicle.

1 Inductive charging system

The energy is transmitted by two coupled coils. The primary coil is located in the parking lot and can be installed level with the road surface. The secondary coil is mounted on the underbody of the vehicle. The primary coil is supplied with a high-frequency electrical alternating voltage. This must be generated from an inverter. Typical frequencies of inductive energy transfer systems for electric vehicles are between 79—90 kHz[2]. As soon as the secondary coil in the vehicle is brought over the primary coil, the field of the primary coil couples into the secondary side. This leads to a current flow in the secondary side. After the current is rectified, it can be used to charge the battery of the electric vehicle. Since alternating voltages generate a lot of reactive power in a coil, these must be compensated with a capacitor. The capacitor can be introduced parallel or series to the coil. Since there is a primary coil and a secondary coil in an inductive charging system, this results in 4 topologies[1].

The first topology is the 1p2p topology is shown in Fig. 1. The capacitor is connected in parallel (p) with the primary coil (1) and the secondary coil (2). This results in the second topology to the 1s2s topology, which is shown in Fig. 2. In this case the capacitors are connected in series (s) to the respective coil. The next two topologies are the 1p2s and 1s2p topologies. In the 1p2s topology, the primary side is compensated in parallel and the secondary side is compensated in series. It is exactly the other way round with the 1s2p topology, as shown in Fig. 3 and 4.

To charge the electric vehicle, the 1s2s topology has the greatest advantages. The serial compensation on the secondary side results in a constant current source. As the battery voltage increases during charging, the 1s2s topology does not require the primary side to readjust the power source to meet the greater voltage demand of the battery. The following findings are applied based on a 1s2s topology[5].

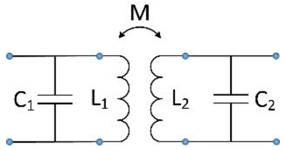

Fig.1 1p2p

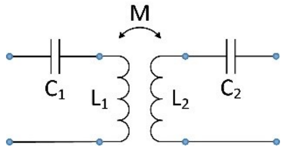

Fig.2 1s2s

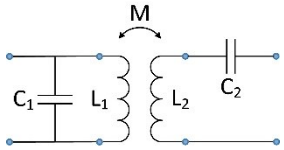

Fig.3 1p2s

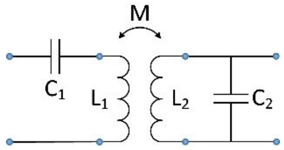

Fig.4 1s2p

2 Coupling

The coupling determines how much field energy flows from the primary side into the secondary side. For safe and efficient power transmission, the transmission line is designed for a certain coupling range. Typical values for coupling are between 0.25 and 0.35[3]. With ideal coils, the coupling is calculated to[4]:

$$k=\sqrt{1-\frac{L_1'}{L_1}} \tag{1}$$

where: L_1 is the measured inductance at the primary coil in position with the secondary coil, the secondary coil is in open circuit; Correspondingly, L_1' is the inductance of the primary coil with the secondary coil shorted. This measurement method determines the influence of the secondary coil on the primary coil. Disturbances are avoided, since the position, and thus parasitic effects, does not change. Such a measuring method is very complex. The primary side has to be separated from the compensation capacitor and connected to a measurement device. In addition, the secondary side must also be disconnected from the compensation capacitor. Two measurements must be made with the secondary side shorted and the secondary side opened at the transmission frequency. Therefore this procedure only takes place in laboratories.

For the operation of an inductive energy transfer charger for an electric vehicle the exact coupling factor is not interesting. An estimation of the current coupling is much more sufficient to enable safe and efficient charging.

3 Transfer function of a 1s2s topology

In the following, the relationships of the voltages of an inductive power transmission line are presented (See Fig. 5).

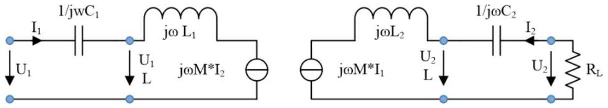

Fig.5　Equivalent circuit of transmission path

From the source [1] the equation can be taken. The equation describes the voltage transfer function:

$$\left|\frac{U_2}{U_1}\right|=\frac{R_L}{\omega_0 k\sqrt{L_1 L_2}} \tag{2}$$

The function is only valid if $\omega_0=\omega_1=\omega_2$. Thus, the primary side and the secondary side must be tuned to the same frequency. This is desired for an efficient power transmission line. The equation is used to describe a relationship of the coupling and the load resistance. Furthermore, the characteristic resistance for the frequency ω_0 can be taken from the source [1] to:

$$R_{L,\mathrm{ch}}\approx k\omega_{r0}L_2 \tag{3}$$

The characteristic resistance describes the most efficient point of energy transfer. For 1s2s inductive charging system, the characteristic resistance should be targeted as a load, but should not be undercut, because then the resonant frequency of the charging system changes. The input impedance at the system can also be taken from the source [1].

$$|Z_{\mathrm{IN}}|=\frac{U_1}{I_1}=\frac{\omega_0^2 k^2 L_1 L_2}{R_L} \tag{4}$$

The used circuit has a primary side with an inductance of 35 μH and is compensated with a 100 nF capacitance. The secondary side has a 55 μH primary inductance and a 62 nF capacitance. This results in a natural frequency of 85kHz for the primary side and 86kHz for the secondary side.

4 Rectifier

The rectifier is located between the secondary coil with the compensation capacitor and the battery. A full bridge rectifier is used for efficient charging. This allows the maximum power to be transferred from the system. However, for the position detection, a rectifier is needed that can cut back power. Therefore, the rectifier is equipped with a Transistor Q_1 to obtain two operating points, as shown in Fig. 6.

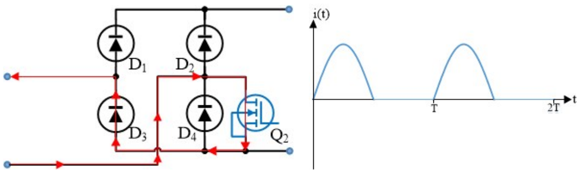

Fig.6　Rectifier with turned on transistor and current waveform

When Q_1 is turned off, this is a full-bridge rectifier. The equations apply to:

$$I_{\mathrm{bat,FB}}=\frac{1}{T}\int_0^T|i_S(t)|\mathrm{d}t=\frac{2\sqrt{2}}{\pi}I_{\mathrm{S,eff}}\approx 0.9I_{\mathrm{S,eff}} \tag{5}$$

$$U_{\mathrm{bat,FB}}=\frac{2\pi}{\sqrt{2}}U_{\mathrm{S,eff}}\approx\frac{1}{0.9}U_{\mathrm{S,eff}} \tag{6}$$

The transistor Q_1 can be used to short-circuit the diode D_4. Negative half-waves are thus short-circuited via the transistor through the diode D_3. This ensures a continuous current flow, so that the field in the coil L_2 is sustained. The output voltage of the rectifier corresponds to that of a 1-diode rectifier. Thus, the current and voltage equations apply to:

$$I_{\mathrm{bat,HB}}=\frac{1}{T}\int_0^T\left|i_{\mathrm{S}}(t)\right|\mathrm{d}t=\frac{\sqrt{2}}{\pi}I_{\mathrm{S,eff}}\approx 0.45I_{\mathrm{S,eff}}\tag{7}$$

$$U_{\mathrm{bat,HB}}=\frac{\pi}{\sqrt{2}}U_{\mathrm{S,eff}}\approx\frac{1}{0.45}U_{\mathrm{S,eff}}\tag{8}$$

This allows the power behind the rectifier to be reduced by a factor of four, when the rectifier is switched in half-bridge mode. The diodes are considered ideal and lossless in this paper.

5 Estimation of coupling by using a resistor

To estimate the coupling of the electric vehicle, the load behind the rectifier is simulated by a resistor. The traction battery is not suitable as a load, because the voltage of the battery changes strongly depending on the state of charge (SOC). Therefore, the battery must be disconnected from the charging system and a defined resistor must be connected into it. The resistance should be as close as possible to the characteristic resistance. This additionally depends on which type of rectification is used. This results in the following for the load resistance for a full-bridge rectifier:

$$P_2=P_{2,\mathrm{DC}}\tag{9}$$

$$\frac{U_2^2}{R_L}=\frac{U_{2,DC}^2}{R_{L,\mathrm{DC}}}\tag{10}$$

$$R_L=\frac{U_2^2}{U_{2,\mathrm{DC}}^2}R_{L,\mathrm{DC}}\tag{11}$$

$$R_L=0.9^2R_{L,\mathrm{DC,FB}}\tag{12}$$

For a HB-rectifier the results in a resistance are:

$$R_L=0.45^2R_{L,\mathrm{DC,HB}}\tag{13}$$

This means that positioning should be carried out in half-bridge mode, because less Power has to be dissipated from the resistor. The voltage at the resistor $U_{2,\mathrm{DC}}$ results for equation (2) with equation (7) to:

$$U_{2,\mathrm{DC}}=\frac{R_L U_{1,\mathrm{DC}}}{0.45^2\omega_0 k\sqrt{L_1L_2}}\tag{14}$$

$$U_{2,DC}=\frac{0.45^2R_{L,\mathrm{DC,HB}}U_{1,\mathrm{DC}}}{0.45^2\omega_0 k\sqrt{L_1L_2}}\tag{15}$$

$$U_{2,\mathrm{DC}}=\frac{R_{L,\mathrm{DC,HB}}U_{1,\mathrm{DC}}}{\omega_0 k\sqrt{L_1L_2}}\tag{16}$$

Using equations (4) and (8), the voltage $U_{2,\mathrm{DC}}$ can be given as a function of the current $I_{1,\mathrm{DC}}$:

$$U_{2,\mathrm{DC}}=\frac{R_{L,\mathrm{DC,HB}}}{\omega_0 k\sqrt{L_1L_2}}\times\frac{U_{1,\mathrm{DC}}\times I_{1,\mathrm{DC}}}{I_{1,\mathrm{DC}}}\tag{17}$$

$$U_{2,\mathrm{DC}}=\frac{R_{L,\mathrm{DC,HB}}}{\omega_0 k\sqrt{L_1L_2}}\times\frac{\omega_0^2k^2L_1L_2\times I_{1,\mathrm{DC}}}{R_{L,\mathrm{DC,HB}}\times 0.45^2}\tag{18}$$

$$U_{2,\mathrm{DC}}=\frac{I_{1,\mathrm{DC}}}{0.45^2}\omega_0 k\sqrt{L_1L_2}\tag{19}$$

This results in 2 equations (16 and 19) for the relationship between the voltage across the resistor and the coupling. Equation 16 results for a constant voltage source at the primary side. If a constant current source supplies the primary side, equation 19 is suitable. A constant voltage source leads to the fact that with a 1s2s path, the voltage in the secondary side becomes very large with poor coupling. In addition, the current on the primary side increases greatly.

Therefore, this option is not open-circuit proof and is only suitable for position detection to a limited extent. With a constant current source at the primary side, the voltage on the secondary side is limited. This makes the system open-circuit proof and makes it very suitable for using the method even by poor couplings.

7 Measurement result

The measurements were performed on an existing system. The following data should give an idea of how the system can be used. The Systems can move one of the coil pair in the x-axis and y-axis. Here only the x-axis is presented, because the results of the y-axis is similar. The z-axis was not investigated. Lower vehicles will couple better. Therefore, the counter coupling could be higher than the minimum coupling that is required. This has to be evaluated especially for low vehicles.

In Fig. 7, the course of the coupling can be seen. The system was aligned in such a way that the best possible coupling of 0.26 is achieved. Better couplings are not possible due to the distance between the vehicle's underbody and the road surface. Then the secondary coil was moved in the direction of the vehicle. This corresponds to a reverse parking process.

In this case, the coupling decreases with greater distance. The voltage at $R_{L,\mathrm{DC,HB}}$ drops in the same way as the coupling. At a distance of 270 mm, the coils start counter-inducing. Thus the coupling increases again up to a value of 0.13. That means, the system is unique for a coupling range above 0.13 and a coupling factor can be assigned to each voltage in this range. For couplings below 0.13, more than one position can be assigned to the vehicle.

For example, with a coupling of 0.1, the vehicle could be located at position 170 mm, 370 mm, and 500 mm. Since in this system a minimum coupling of 0.18 and higher is required to start the charging process, the system can make a statement as to whether the vehicle is sufficiently well positioned for charging.

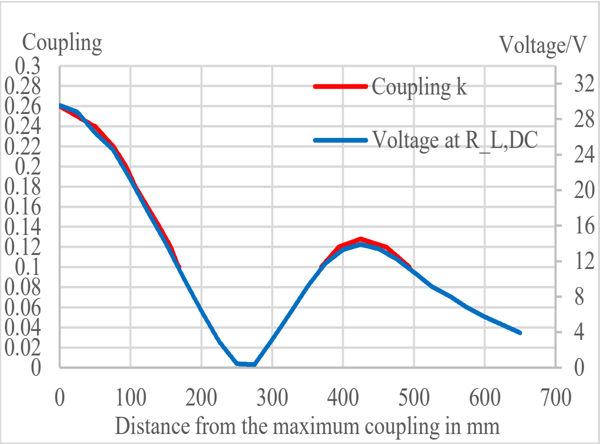

Fig.7 The change of coupling with increasing distance from the optimized coupling

8 Conclusions

The method that is presented in this paper can approximate the coupling of the coils of an inductive charging system for electric vehicles in the necessary area. The method can only show, if the vehicle is positioned correctly and therefore can only be used as a safeguard. It is not suitable to show the driver, how he has to correct the position of the vehicle, for a better coupling. There for a combination with another system has to be integrated. The system presented by Dean Martinović, is very suitable for this **Ref.** [6]. In the paper special sensors are used to detect the field and position of the primary side.

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