Improvement means of charge batteries for electric car

V V Ivanov, S V Myatezh, I V Dubinina, I G Savluk

Novosibirsk State Technical University, 20, Karla Marksa ave., Novosibirsk, 630073, Russia

E-mail: ivanov.etk@yandex.ru

Abstract. This article discusses different means to charge electric car batteries, identifies trends in the development of a non-contact method of energy transfer, the calculation of the electrical parameters of the inductors for the implementation of the contactless charge of the battery of the electric vehicle. Produced simulation magnetically coupled system to confirm the theoretical results.

1. Introduction
Currently, the electric vehicle has many advantages and opportunities for distribution, given their environmental friendliness [1]. However, electric vehicles also have a serious drawback, which is the problem of charge of an electrical energy source. This problem hinders their development compared to vehicles with internal combustion engines running on gasoline or diesel fuel. In order to be able to compete with vehicles with internal combustion engines, manufacturers pay serious attention to the problem of improving battery charging systems as traditional sources of energy for electric vehicles [2].

However, these methods have a common disadvantage – they do not allow replenishing the electric energy of the battery when the electric vehicle is moving and require it to stop completely. At this time, the electric car is inactive and cannot be used. One of the solutions to this disadvantage is to transfer electrical energy to the electric vehicle during its movement. The principle of this technology is based on the interaction of two inductors. One of them is under the asphalt, and the second is on an electric vehicle. An air transformer is the simplest device for wireless power transmission [3].

The usefulness of the method of non-contact transmission of electrical energy is proved in [4]. Despite the proven promise and obvious convenience of practical application, experts around the world are working on improving this technology.

This article is aimed at establishing rational geometrical ratios of the sizes of the primary and secondary coils of the transformer and their relative positions for powering electric vehicles in real conditions.

2. System Resonance Mode
A transformer is a static device that has two or more inductively coupled coils and provides contactless transmission of electrical energy due to inductive coupling between these coils [5]. A coil connected to a source of electrical energy is called primary, and a coil connected to a consumer of electrical energy is called secondary.
The air transformer is the simplest device for non-contact energy transfer. The primary and secondary coils of the transformer are not directly connected. Energy transfer is through mutual induction. For improving the range of energy transfer, resonance is used in the circuit of the primary and secondary coils, while the transmitter and receiver are tuned to the same frequency. For this, coils should represent single-layer spirals. The efficiency of the system also increases due to changes in the waveform [6].

The disadvantage of an air transformer is that energy is transmitted through the airspace, and for this, it is necessary to create large currents to create a magnetic flux. These large currents cause losses in the conductors. It is known from the theory of an air transformer that a significant component of the current is reactive.

The operation of an air transformer can be optimized if a part of its current, which has a reactive component, is compensated by a capacitive current taken from a capacitor. This phenomenon is called resonance. The resonance of the currents helps the air transformer to achieve the optimal mode, and, subsequently, it is necessary to adhere to the compensation model of the air transformer [7].

Table 1. List of variables for calculation

| Parameter/Name                        | Designation | Units  | Value          |
|---------------------------------------|-------------|--------|----------------|
| Input voltage/frequency               | \( f \)     | kHz    | 5–100          |
| Angular frequency                     | \( \omega \) | sec\(^{-1}\) | \( 2\pi f \)  |
| The number of turns of the primary inductor | \( N_1 \) | -      | 15             |
| The number of turns of the secondary inductor | \( N_2 \) | -      | 15             |
| Air gap between coils                  | \( h \)     | m      | 0.25           |
| The radius of the primary inductor     | \( r_1 \)   | m      | 0.25           |
| Radius of the secondary inductor      | \( r_2 \)   | m      | 0.25           |
| Conductor diameter                    | \( d \)     | mm     | 10             |

We calculate the cross-sectional area of the conductor according to the formula (1):

\[
S = \pi \left( \frac{d}{2} \right)^2
\]

\[
S = 3.14 \cdot \left( \frac{10}{2} \right)^2 = 78.5 \text{ mm}^2
\]

The length of the conductor in the coil is:

\[
l = 2\pi rN = 2 \cdot 3.14 \cdot 0.25 \cdot 15 = 23.56 \text{ m}
\]

By the formula (2) we find the resistance on the coils:
\[ R = \rho \frac{l}{S} \]  

(2)

Where \( \rho = 0.017 \ \frac{Ohm \cdot mm^2}{m} \) - electrical resistivity of copper conductors [8];

\( l \) - conductor length;

\( S \) - cross-sectional area.

When, \( R = 0.017 \cdot \frac{23.56}{78.5} = 0.005 \ \text{Ohm} \).

![Figure 2](image)

**Figure 2.** The mutual arrangement of the primary and secondary windings

We will calculate the mutual induction:

\[ M = \mu_0 \sqrt{r_1 r_2} \cdot f(k) \]  

(3)

when \( \mu_0 = \mu = 4 \cdot \pi \cdot 10^{-7} \ \frac{H}{m} \) - absolute magnetic permeability;

\( k \) - coupling coefficient;

The dimensionless quantity is determined by the mutual position of the coils and is equal to:

\[ k^2 = \frac{4 \cdot r_1 \cdot r_2}{h^2 + (r_1 + r_2)^2} = \frac{4 \cdot 0.25^2}{0.25^2 + (0.25 + 0.25)^2} = 0.8 \]

The function of the quantity is found from the formula (4):

\[ f(k) = \left( \frac{2}{k} - k \right) K - \frac{2}{k} E \]  

(4)

when \( k = +\sqrt{k^2} \);

\( K \) - the elliptic integral of the first kind;

\( E \) - the elliptic integral of the second kind.

Elliptic integrals are functions \( k^2 \). Для \( k^2 = 0.8 \) elliptic integral of the first kind \( K(k^2) = 2.257 \), the elliptic integral of the second kind \( E(k^2) = 1.178 \).
Then, \( M = \pi \cdot 10^{-7} \cdot \sqrt{0.25 \cdot 0.25 \cdot 0.4} = 6.3 \cdot 10^{-5} \ H \)

\[
f(k) = \left( \frac{2}{0.894} - 0.894 \right) \cdot 2.257 - \frac{2}{0.894} \cdot 1.178 = 0.4
\]

According to Figure 3, it is possible to make equations according to the second Kirchhoff law [9].

\[
\begin{align*}
[(R_1 + j\omega \cdot (I_4 - M)) \cdot I_1 + j\omega \cdot (I_1 + I_2)] & = U_1 \\
[(R_2 + j\omega \cdot (L_2 - M)) \cdot I_2 + j\omega \cdot (I_1 + I_2) + Z_n \cdot I_2] & = 0
\end{align*}
\]

We substitute the known variables into this system of equations and obtain:

\[
\begin{align*}
[(0.005 + j\omega \cdot (4 \cdot 10^{-4} - 6.3 \cdot 10^{-5})) \cdot I_1 + j\omega \cdot 6.3 \cdot 10^{-5} \cdot (I_1 + I_2)] & = 500 \\
[(0.005 + j\omega \cdot (4 \cdot 10^{-4} - 6.3 \cdot 10^{-5})) \cdot I_2 + j\omega \cdot 6.3 \cdot 10^{-5} \cdot (I_1 + I_2) + 10 \cdot I_2] & = 0
\end{align*}
\]

in reply \( I_1 = 303.5 \ A; I_2 = 45.5 \ A. \)

3. Simulation

Figure 4 shows the model of an air transformer. The assembled model allows obtaining time diagrams of currents and voltages and the values of active and reactive powers using the unit, as well as calculate the efficiency of the system. Magnetically coupled coils are modelled by the Mutual Inductance block, where the intrinsic and mutual inductances and the active resistance of the coils are specified [10].

**Figure 3.** Diagram of an air transformer

**Figure 4.** Model of an air transformer in the Matlab Simulink interactive program in resonance mode
The capacitor included in the circuit helps the air transformer to achieve the optimum operating mode and thereby reduce the loss of electrical energy. The resonant frequency is $f_0 = 10 \text{ kHz}$. The capacitor capacity required for resonance is:

$$C = \frac{1}{(2\pi f_0)^2 \cdot L} = \frac{1}{(2 \cdot \pi \cdot 10000)^2 \cdot 4 \cdot 10^{-4}} = 632.9 \text{ nF}$$

Figure 5 shows a timing diagram of the power supply voltage. The effective voltage value of the sinusoidal shape is 86.5 V.

Figure 6 shows a comparative time diagram of the currents of the primary circuit $I_1(t)$ with and without a capacitor included in the circuit.

Based on the phenomenon of resonance of currents, the optimal mode of operation of the system is obtained, which allows reducing the current by 7.5 times from 305 A to 40.73 A. The efficiency of a magnetically coupled system rises to 95.36%.
According to the phenomenon of current resonance, the operation mode of a magnetically coupled system is optimized. The capacitor in the circuit allows compensating for the current having a reactive component. In this mode, the reactive power is 4950 W.

4. Conclusion
During the calculations, the main characteristics of the magnetically coupled system became known. Flat spiral coils have 15 turns, the cross-sectional diameter of the conductors is 10 mm, the air gap between the coils is 0.25 m. As a result of the calculations, the following data were obtained: the active resistance of the coils is $R_1 = R_2 = 0.005 \, \text{Ohm}$; the inductance of the coils is $L_1 = L_2 = 4 \cdot 10^{-4} \, \text{H}$; mutual induction is $M = 6.3 \cdot 10^{-5} \, \text{H}$. These parameters allow, as calculations showed, transmitting power of 5090 W. The efficiency is 90.55%, which can be used for charging the battery of an EV and used in practice.

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