Implementation algorithm and mathematical model of contactless power transmission for powering an electric vehicle

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Abstract. The work is devoted to methods for increasing the energy efficiency of photovoltaic modules. Various algorithms for determining the maximum power points and their application to obtain the maximum possible efficiency when using solar panels are considered. The principles of the operation of algorithms are described, their advantages and disadvantages are indicated. Their comparison was carried out according to the main significant parameters. The most suitable algorithm for application at a weather station has been selected.

1. Introduction
One of the main drawbacks of current electric vehicles is the lack of battery power for long driving. The popularity of the electric vehicle will increase if it becomes possible to replenish its charge while driving. First, the vehicle's weight and dimensions will improve, which will make it more affordable due to the use of a battery with a lower capacity and, accordingly, weight. Secondly, the range of electric vehicles will improve due to the creation of charge lanes on certain sections of the road.

The non-contact method of energy transmission is based on the phenomenon of electromagnetic induction. The main problem is the weak inductive coupling between the coils due to the large air gap between them (from 10 cm or more). Because of this, the transmission efficiency decreases, which depends on the relative position and orientation of the coils in space.

The following is an algorithm for the implementation of contactless energy transfer:
• calculation of mutual induction of two circular contours
• calculation of air transformer
• calculation of the resonance mode in the system
• calculation of parameters of inductors
• computer simulation of the system
• simulation of the resonant mode of operation of circuits
2. Resonance mode in the system

An air transformer is the simplest device for wireless power transmission. The primary and secondary windings of the transformer are not directly related. Energy transfer is carried out through mutual induction. To increase the range of energy transmission, resonance is used in the circuit of the primary and secondary windings, while the transmitter and receiver are tuned to the same frequency. The coils should be single-layer coils. The efficiency of the system is also increased by changing the waveform.

The disadvantage of an air transformer is that energy is transmitted through air space, and for this it is necessary to create large currents to create a magnetic flux. These high currents cause conductor losses. As is known from the theory of an air transformer, a significant component of the current is reactive in nature. The operation of an air transformer can be optimized if the part of its current, which has a reactive component, is compensated by a capacitive current taken from the 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 mode of the air transformer.

There are 4 main types of resonant circuits, depending on how the capacitor is connected to the inductor: series-series, series-parallel, parallel-series and parallel-parallel.

Resonance of currents (parallel resonance) is a resonance that occurs in a parallel oscillatory circuit when it is connected to a voltage source, the frequency of which coincides with the resonant frequency of the circuit [1, 2, 11, 12].

There is a parallel oscillatory circuit consisting of a resistor \( R \), an inductor \( L \) and a capacitor \( C \). The circuit is connected to an alternating voltage source with a frequency of \( \omega \). The resonant frequency of the circuit is found by formula 1.

\[
\omega_p = \frac{1}{\sqrt{LC}}
\]  

Figure 1 shows a system of magnetically coupled coils with a parallel resonance circuit.

![Figure 1](image-url)

**Figure 1.** Electrical circuit diagram of contactless power transmission.

A parallel-parallel resonant circuit is a parallel connection of capacitors \( C_1, C_2 \) and inductors \( L_1 \) and \( L_2 \). Voltage \( u_1(t) \) at the output of the high-frequency inverter in shape is rectangular. Current \( i(t) \) that flows through the coil inductance \( L_1 \) of the primary winding, creates an alternating magnetic flux \( F_1(t) \). This magnetic flux penetrates the turns of both coils and induces EMF \( e_1(t) \) and \( e_2(t) \) in them. Under the action of the induced EMF of induction \( e_2(t) \) in the inductor \( L_2 \), a current flows in the second winding \( i_2(t) \). The bridge circuit of the VD1-VD4 diode rectifier converts alternating current into direct current. The capacitive filter \( C_f \) smoothes the ripple of the rectified voltage [3].
3. Calculation of inductance coil parameters

To calculate the parameters, set some initial conditions. Table 1 lists the variables used in the calculation.

| Parameter Name            | designation | Units measurements | value   |
|---------------------------|-------------|--------------------|---------|
| Input voltage frequency   | f           | kHz                | 5 - 100 |
| Angular frequency         | ω           | rad/s              | 2πf     |
| Number of primary coil turns | N₁         | -                  | 15      |
| Number of primary coil turns | N₂         | -                  | 15      |
| Air clearance between coils | h           | m                  | 0.25    |
| Primary coil radius       | r₁          | m                  | 0.25    |

Calculate the cross-sectional area of the conductor using the formula (2)

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

\[ S = 3.14 \cdot 10^{-2} = 78.5 \text{ mm}^2 \]

Length of conductor in coil is equal to:

\[ l = 2\pi rN \]

\[ l = 23.56 \text{ m} \]

Find resistance on the coils:

\[ R = \rho \frac{l}{S} \]

Where \( \rho = 0.017 \text{ Ohm mm}^2 / \text{m} \)

electrical resistivity of copper conductors.

I is the length of the conductor;

S is the cross-sectional area.

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

Let's calculate the interaction:

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

Where \( \mu_0 = 4 \cdot \pi \cdot 10^{-7} \text{G} \)

absolute magnetic permeability;

k is the communication coefficient;

Dimensionless value k is determined by mutual position of coils and is equal to:

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

value function k:

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

Where \( k = \sqrt{k^2} \).

K is an elliptical integral of the first kind;

E is an elliptical integral of the second kind.

Elliptical integrals are functions of \( k^2 \). For \( k^2 = 0.8 \)
elliptical integral of the first kind \( K (k^2) = 2.257 \),
elliptical integral of the second kind \( K (k^2) = 1.178 \)

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

Then, \( M = 4 \cdot \pi \cdot 10^{-7} \cdot \sqrt{0.25 \cdot 0.25 \cdot 0.4} = 6.3 \cdot 10^{-5} \, \text{Gn} \)

According to Figure 2, the equations can be made according to the second p. Kirchhof.

\[
[(R_1 + j \omega \cdot (L_1 - M)) \cdot I_1 + j \omega M \cdot (I_1 + I_2)] = U_1

[(R_2 + j \omega \cdot (L_2 - M)) \cdot I_2 + j \omega M \cdot (I_1 + I_2) + Z_n \cdot I_2] = 0
\]

In this system of equations we substitute the known variables and obtain:

\[
[(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
\]

Using the Mathcad program, it is easy to find two unknowns, which are ultimately equal to \( I_1 = 303.5 \, \text{A}; \ I_2 = 45.5 \, \text{A} \)

4. Description of computer model in resonance mode of circuits operation

Simulation of the magnetically connected system is carried out in the interactive environment Matlab Simulink. Table 2 lists the main parameters used to build the model [4].

| Parameter Name                        | Designation | Units of Measure | Value  |
|--------------------------------------|-------------|------------------|--------|
| Amplitude value supply voltage       | \( U_m \)   | V                | 500    |
| Input voltage frequency              | \( f \)     | kHz              | 10     |
| Primary inductance windings          | \( L_1 \)   | mkGn             | 400    |
| Primary inductance windings          | \( L_2 \)   | mkGn             | 400    |
| Mutual inductance                    | \( M \)     | mkGn             | 63     |
| Active resistance of the primary winding | \( R_1 \) | mOm              | 5      |
| Active resistance of the secondary winding | \( R_2 \) | mOm              | 5      |

Figure 3 shows a model of an air transformer in resonance mode. The assembled model allows you to obtain time diagrams of currents and voltages using the Scope block (Oscilloscope), obtain the values of active and reactive power using the Power block, and calculate the system efficiency. Magnetically coupled coils are modeled by the Mutual Inductance block, where the self and mutual inductances and active resistances of the coils are set [5]. The currents in the branches and voltages on the circuit elements are measured by the Current Measurement and Voltage measurement blocks. The capacitor included in the circuit helps the air transformer achieve optimal operation and thus reduce
the loss of electrical energy. The resonant frequency is \( f_0 = 10 \text{ kHz} \). The capacitance of the capacitor required for resonance is equal to:

\[
C = \frac{1}{(2\pi f_0)^2 \cdot L} = \frac{1}{(2 \cdot \pi \cdot 10000)^2 \cdot 4 \cdot 10^{-3}} = 632.9 \text{ nF}
\]

Thus, the system in the resonant mode has the following parameters: \( R_1 = R_2 = 5 \text{ m\Omega} \); \( L_1 = L_2 = 4 \cdot 10^{-4} \text{ H} \); \( M = 6.3 \cdot 10^{-5} \text{ H} \); \( Z_0 = 101 \text{ Ohm} \); \( C = 632.9 \text{ nF} \); \( f_0 = 10 \text{ kHz} \).

Figure 3 shows a diagram of an air transformer in resonant operation.

![Figure 3. Model of an air transformer in resonance mode](image)

With the resonance of currents made with a capacitor in the primary circuit, the voltage and current in the secondary circuit remain unchanged. An additional verification of the calculations in the equivalent T-shaped equivalent circuit was also carried out [6].

The T-shaped equivalent circuit showed similar results, performed according to a different method, which also indicates the reliability of the values obtained.

Using the phenomenon of current resonance, the operating mode of the magnetically coupled system is optimized. The capacitor in the circuit makes it possible to compensate for the current having a reactive component. In this mode, the reactive power is 4950 W.
5. Conclusion

Thus, an algorithm and a mathematical model have been obtained that demonstrate an increase in efficiency in the system of wireless transmission of electrical energy to an electric vehicle. The results of simulation modeling of an electric air transformer operating in a resonant mode are presented.

In the course of 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. Because of 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 $L_1 = L_2 = 4 \times 10^{-4} \text{ Gn}$; mutual induction is $M = 6 \times 10^{-5} \text{ Gn}$.

These parameters allow as the calculations showed, transmit power 5090 W. The efficiency is 90.55%, which can be used to charge the battery of an electric vehicle and be used in practice.

Determined, in the course of simulation, the transmission efficiency of the magnetically coupled system is 90.55%. The effective value of the input voltage is 85.6V, the effective value of the primary winding current is 305A, the effective value of the secondary winding current is 46.73A.

It was found that at a frequency of 10 kHz, the required value of the capacitance of the capacitor to ensure the resonant mode is $C = 632.9 \text{ nF}$. Resonance significantly reduces the primary current by 7.5 times from 305A to 40.73A and increases the efficiency to 95.36%.

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