Electromagnetic analysis of a contactless charging station for electric vehicles

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Abstract. This report examines one of the many possible solutions of dynamic and static mode contactless power transfer, which determines the future of the automotive industry. Computer analysis of a contactless charging station for electric vehicles in certain frequency range and displacement between the transmitting and receiving coils are presented. Conceptual prototype design of 30 kW power transfer station is described in detail. Some optimization approach is also noted. The results are compared with the real experiments of prototype for a contactless charging station.

1. Introduction
A number of economic and environmental factors with increasing significance in recent years, have necessitated the search for innovative solutions in the automotive industry. There are many researches and developments in hybrid car engines - those powered by hydrogen fuel cells and many others but most of them cannot be applied in practice to compete with the internal combustion engine. Cost, technological sustainability, safety and ease of use of an innovative solution are the key factors for its market popularization. By this reason, one of the main practical factors for the mass "put on the road" of the electric car is the maximum mileage with one charge that can be realized and the method of charging with the best technical and operational parameters. Development of the element base and the methods for control of power electronic devices, the contactless transmission of electric power or wireless power transmission (WPT) is increasingly used in everyday life like domestic appliances, industrial technologies, mobile devices, medical equipment and transport. The main advantage of this technology is the elimination of power cables, the use of different standards in couplings and the depreciation of power circuits. This issue is especially serious when charging the batteries of electric vehicles, where in addition to the lack of cables and connectors, wireless technology produces a natural galvanic separation, which is extremely important to ensure safety [1-5]. The main purpose of the manuscript is to present a developed power electronic system for contactless charging of electric vehicles, operating in static and dynamic mode. Another task is to demonstrate practical aspects of the application of this relatively new technology, related to its advantages, as well as some of its disadvantages at present.

2. Topology and construction
Until recently, the main problem was the relatively low efficiency (ECE), due to both the imperfections of the semiconductor devices with which the converters are built, and the non-optimally designed electromagnetic systems for contactless transmission. Modern MOS and IGBT transistors
have very good performance and thus it is possible to design high-frequency converters with high energy density. An interesting feature of the considered device is the system for transferring maximum power, which the charging station provides – over 30 kW in continuous operation. In practice, such levels of transferred power make this prototype economically adequate compared to many companies producing contactless charging systems for electric vehicles such as: NISSAN, PRIMOVE, SIEMENS, WAMPFLER etc. [2-6].

Figure 1 shows the topology of the power electronic system of the device. As the prototype is designed to test and demonstrate static and dynamic operation (while the vehicle is moving), it is necessary to use an advanced model of a standard full bridge converter [1, 7-11]. For this purpose, one arm of the converter operates continuously (both static and dynamic), while the other four are connected to each of the inductive power transmission (IPT) windings. The main advantage of this type of full bridge modification is the reduction of the total number of IGBT modules required for the implementation of the system – instead of four separate converters, each with two modules (eight modules in total), in this case 5 modules are used. In other words, instead of using four separate full-bridge inverters, the designed prototype uses only one modified five-link inverter.

Of course, the main unit in the IPT station is the power transformer with a weak magnetic connection, due to the use of an air gap. It is known from the literature that the process of designing this type of transformer is focused on the specifics of the geometry and dimensions, the range of change of the mismatch, the mechanical construction, the concentration and orientation of the electromagnetic field and others.

![Figure 1](image.png)

**Figure 1.** Selected power electronics topology of the on-route charging of EVs.

Figure 2 presents the results for evaluating the influence of the aluminum shield on the IPT windings obtained by modeling the electromagnetic system and computer simulations. The main objectives of this simulation are to assess the level of influence of the electromagnetic field on nearby objects, in accordance with the requirements of ICNIRP.
The design of the magnetic system, consisting of a transmitting coil and a model of the distribution of ferrite rods, is shown in figure 3. The main role in increasing efficiency is played by the value of the effective current density in the coil conductor (indirectly through copper losses) and the type of the material of the ferrite rods. In addition, the weight of the receiving coil (located in the EV) also affects the overall efficiency.

Table 1 shows the main parameters of the developed IPT transformer and their change for different values of the air gap and at a frequency that provides Zero Current Switching (ZCS) mode of the semiconductor devices of the inverter (IGBTs). The values thus determined are measured by connecting the primary and secondary windings in series - in one direction ($L_{SER}$) and vice versa ($L_{PAR}$) [9, 12].

| ZCS Frequency | Vertical Gap | 14.4 kHz | 13.8 kHz | 13.3 kHz | 13.0 kHz |
|---------------|--------------|----------|----------|----------|----------|
| $N_2 / N_1$   | 55 mm        | 1.63     | 1.63     | 1.625    | 1.63     |
| Coupling coefficient, $k$ | 65 mm        | 0.613    | 0.556    | 0.508    | 0.465    |
| $M$, µH       | 70 mm        | 83.65    | 73.7     | 66       | 59.43    |
| $L_{1t}$, µH  | 79           | 76.7     | 75       | 73.6     |
| $L_{2t}$, µH  | 236          | 229.4    | 225      | 221.9    |
| $L_{1t} + L_{2t}$ ($L_{SER}$), µH | 225          | 453.2    | 431      | 413.8    |
| $L_{1t} - L_{2t}$ ($L_{PAR}$), µH | 147.4        | 158.4    | 167      | 176.1    |
| $L_m$, µH    | 51.48        | 45.35    | 40.62    | 36.57    |
| $L_{11t}$, µH| 27.52        | 31.35    | 34.38    | 37.03    |
| $L_{22t}$, µH| 152.4        | 155.7    | 159      | 162.5    |

The main parameters of the magnetic system are determined by the following ratios:
\[ M = L_m \left( \frac{N_2}{N_1} \right) = \frac{|L_{ser} - L_{par}|}{4}; \]  

(1)

\[ k = \frac{M}{\sqrt{L_1 L_2}}; \]  

(2)

\[ L_{11} = L_1 - L_m; \]  

(3)

\[ L_{22} = L_2 - L_m \left( \frac{N_2}{N_1} \right); \]  

(4)

\[ L_{ser} = L_1 + L_2 + 2M; \]  

(5)

\[ L_{par} = L_1 + L_2 - 2M, \]  

(6)

where \( M \) is magnetic coupling coefficient; \( L_m \) – magnetized inductance; \( N_1 \) and \( N_2 \) – respectively the number of turns of the primary and secondary windings; \( k \) – coupling coefficient; \( L_1 \) and \( L_2 \) – inductances respectively primary and secondary windings of the transformer.

3. Output power regulation techniques

In the specific case, the frequency shift control method of the converter is used to adjust the output power. Characteristic of this method is that it allows a wide range of changes in the output parameters of the power electronic device depending on the air gap between the windings and their axial displacement. The condition for controlling the power of a continuous load circuit is defined as follows:

\[ V_{HF} = \frac{V_d 2\sqrt{2}}{\pi}; \]  

(7)

\[ I_{HF} = \frac{V_{HF} \cos \varphi}{R}; \]  

(8)

\[ P = \frac{V_{HF}^2 \cos^2 \varphi}{R}; \]  

(9)

\[ P = \frac{V_{HF}^2}{R} \frac{1}{1 + Q^2 \left( \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)^2}; \]  

(10)

where \( V_d \) is DC supply voltage of the converter; \( V_{HF} \) – high frequency voltage (RMS value); \( I_{HF} \) – high frequency current (RMS value); \( \omega \) – angular control frequency of the converter; \( \omega_0 \) – angular resonant frequency of the AC circuit; \( R \) – is the load resistance adjusted to the output of the inverter, corrected by the corresponding efficiency; \( Q \) – the quality factor of the resonant circuit of the inverter.

In combination of simple PWM or Phase Shift PWM regulation technique the expression for power regulation is:

\[ P = \frac{[V_{HF}(1 - D)]^2}{R} \frac{1}{1 + Q^2 \left( \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)^2}; \]  

(11)

where \( D \) – pulse width coefficient.
Another possible option for the implementation of effective control of the output power of the system is the use of a variable connection factor between the windings by changing the parameters of the compensation components [7, 8]. Figures 4 and 5 show the achieved characteristics (figure 4) and a simulation model for changing the values of the secondary inductance $L_3$ or the secondary capacitor $C_3$, respectively. In practice, the process of switching between different sets of capacitors ($C_3$) or different sets of inductors ($L_3$) can be achieved with the help of pairs of electronic switches - MOSFET or IGBT modules [1, 2, 9 and 11].

![Figure 4. Output DC Voltage vs. Frequency characteristics (a) $C_3$ variable, $L_5 = $ const; (b) $L_5$ variable, $C_3 = $ const.](image)

Figure 4. Output DC Voltage vs. Frequency characteristics (a) $C_3$ variable, $L_5 = $ const; (b) $L_5$ variable, $C_3 = $ const.

![Figure 5. Simulation model in the program environment LTSpice for IPT transformer and output compensation.](image)

Figure 5. Simulation model in the program environment LTSpice for IPT transformer and output compensation.

During the design of the studied system it was possible to transmit energy “on-route” (charging during movement). Figure 6 shows the main parameters describing the process of dynamic charging of the battery of the electric vehicle. The length of the path along which the system does not transmit energy is determined by:

$$L_{off} = (L_{coil} - EPT) + D_{coil}.$$

Transferred energy during the movement is proportional to the speed and $EPT$ area ($\pm 80$ mm):
\[ E_{on} = \int_{-\infty}^{+\infty} E_{P T \text{ area}} \, dx, \]  

where \( E_{P T} \) represents the field of efficient contactless energy transfer. This area is determined by the condition that the efficiency of the magnetic system is over 80%. In practice, this limits the maximum speed during dynamic charging. Another limiting factor is the time constants associated with switching the electronic converter; \( P_{T} \) represents the area of energy transfer, but with significantly lower efficiency; \( C_{S A R E A} \) (coil switching area) is used for starting point for the coils switching algorithm.

Figure 6. Defining the main dynamic charging parameters for contactless power transmission.

The presented method for determining the main dynamic parameters is very useful when it is necessary to test the actual performance of the system in different operating scenarios. On the other hand, it is not suitable for use in a real charging process, but only for testing.

Additional 2D Axisymmetric simulation is performed by using of ©COMSOL Multiphysics. Purpose of this is to find a method for optimization of energy transfer. Figure 7a represents model geometry which in our case has round shape assumed for simplification of the model. Number of coil turns, geometry shape and ferrite cores are chosen to fit with the prototype unit physical dimensions. Initial results showed that there is an optimal operating frequency in efficiency point of view (figure 7b). Choosing proper frequency, efficiency of the energy transfer can be optimized by near 2% or even more depending on the gap between the transmitting and the receiving coil [13-16].

On the other hand, the change in the efficiency of the magnetic system is not strongly dependent on the frequency, which is a good prerequisite for optimal control synthesis for the whole device. The subject of the next study is the assessment of the influence of the misalignment of the transmitting and receiving windings, which is common in practice during dynamic charging of electric vehicles.
Figure 7. Simulation results from the modeling of the magnetic system – (a) Model geometry; (b) Energy transfer efficiency at gap of 100 mm.

4. Converter parameters and results

Table 2 shows the main geometrical and electrical parameters of the designed IPT system. Figure 8 shows the current and voltage waveforms of the AC-Bridge diagonal at 85 mm vertical air gap.

| Parameter               | Value                                      |
|-------------------------|--------------------------------------------|
| Nominal Input Power     | 30kVA / 75A / 400V                         |
| Peak Input Power        | 45kVA @ 1min                               |
| Efficiency, %           | up to 92 %                                 |
| Converter Freq., kHz    | 20 kHz ÷ 12 kHz                            |
| Coil dimensions, mm     | 700 mm x 800 mm x 90 mm                    |
| Converter Control       | Frequency shift, Phase shift               |
| Gap, mm                 | 70 ÷ 90 mm                                 |
| Horizontal misalignment, mm | $\Delta X = \Delta Z = \pm 100$ mm |

The dependence of the resonant characteristics of the converter according to the change of the air gap between the windings is shown in figure 9a and 9b. The characteristics establish the need for pre-selection in the design of the system, which is generally reduced to: changing the range of the air gap; selection of a different type of compensation circuit (with the presence of several resonant elements in order to weaken the influence of the load parameters on the mode of operation of the inverter); possibility to change any of the compensating elements in order to achieve optimal operation of the device.

From the characteristics it is established and confirmed, obtained from the modeling of the electromagnetic system, namely that the maximum output power and, accordingly, the greatest inertia of the output voltage of the inverter are obtained at a control frequency of 13 kHz.
Figure 9. Dependences of the main energy parameters of the system on the resonant frequency of the converter – (a) Output IPT Power vs. Resonant frequency at different vertical air gap; (b) Primary IPT coil voltage vs. Resonant frequency at different vertical air gap.

Operation with such a frequency is undesirable from the point of view of user comfort and therefore a magnetic system with other dimensions and parameters should be designed to obtain an optimal transmission frequency above 20 kHz.

The test results of the model charging station are satisfactory both in terms of the mode of operation of the DC/AC inverter with soft switching and good energy performance, and in terms of the influence of the change in the air gap. Further development of this work will be in the direction of improving the magnetic connection between the windings and hence the efficiency of the magnetic system based on model-based optimization of the IPT configuration and the parameters of its core.

5. Conclusion

The theoretical and experimental study of the studied and developed IPT charging station has a very large impact on the overall assessment of the feasibility of practical application. In this regard, one of the obstacles to the development of electro-mobility in general are the limitations associated with the elements for energy storage and the realization of a fast dynamic contactless charge. The content of the work done in this aspect can be summarized as follows:

- Modeling and analysis of electromagnetic processes important in the design of the IPT system.
- Creating basic relationships and interconnections in order to quickly assess and design the system.
- Obtaining characteristics for the purpose of synthesis of robust control of the system
- Prototyping and implementation of the prototype – transmission of 30 kW through an air gap of 7–9 cm and 90% process efficiency.

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