Contactless Battery Charging for EV/HEV

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Abstract. Wireless energy transmission is currently an important concern, considering its multiple applications in modern electrical engineering. There are different topologies in the scientific literature for near field (magnetic or electric) transmission, with emphasis on the efficiency of the process, especially when such systems are used for medium or high power, from 1 to 100 kW, such as required for storage battery charging in electric/hybrid cars. The prototype for wireless charging equipment for storage batteries is presented, designed to allow research and development for optimum constructive solutions for equipping actual EV cars. Wireless battery charging is considered as the only solution for the implementation of driverless vehicles in the near future. The selected constructive solutions were experimentally checked on a test bench fitted with the necessary electrical and electronic facilities to characterize the components and the constructive unit. At the same time, the prototype with a power transfer output of 2 kW will be used to carry out the first wireless charging station at the "Automotive Engineering" Research Centre of the University of Pitesti.

Keywords: Wireless battery charging · Inductive power transfer · Medium frequency inverter · Test bench · Efficiency · Application.

1 Introduction

EV and HEV have storage batteries which can be charged by plugging-in a rectifier to the public low voltage power supply. The charger can be separated from the EV or it can be on board. It always includes an insulating transformer for isolation to the power grid. The solution for direct rectification of power supply voltage (50 Hz) leads to low efficiency, generates a deforming regime, is heavy and has presently been abandoned. In order to increase efficiency and reduce the weight of the charger, its topology has become similar to a SMPS (Switching Mode Power Supply) based on power electronics which also includes an insulating transformer, only it now has reduced dimensions and weight since it operates at high switching frequency of the inverter. However, the plug-in method, in both versions, raises a number of issues, the most important of which is the impossibility of integral automation of the recharging process (the starting and the ending of this process require manual operation by con-

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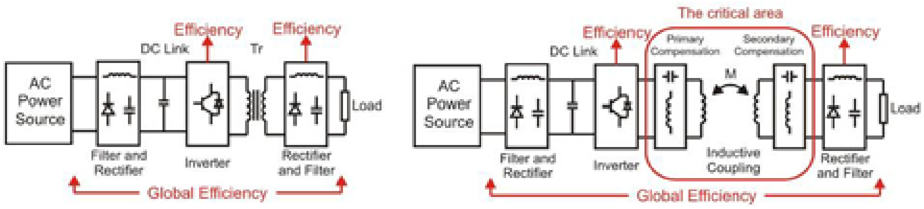
nection to an AC socket, regardless of the environmental conditions: rain or snow), but also the danger not to be neglected for electric shock in case of damage to the power cable [1, 2]. The transition from the plug-in with SMPS to the CPT (Contactless Power Supply), in particular through magnetic induction (IPT - Inductive Power Transfer) is considered, apart from eliminating the disadvantages listed above, as the only solution for the implementation of driverless vehicles in the near future. The paper presents a comparison between the two different state-of-the-art EV battery charging systems, the energy efficiency of the two systems and defines the manner for inductive coupler parameter identification and the effect of magnetic field concentrators etc The prototype for wireless charging equipment for storage batteries is presented next, designed to allow research and development for optimum constructive solutions for equipping actual EV cars. The selected constructive solutions were experimentally checked on a test bench fitted with the necessary electrical and electronic facilities to characterize the components and the constructive unit.

2 Inductive Power Transfer

IPT does not lead to a substantial change of the topology used for modern Plug-in charging. A wireless charging system [3] will be achieved with the same main components (inverter and rectifier) as in Fig.1a, if the separation transformer for galvanic isolation is replaced by an inductive coupler (air-core transformer) with detachable coils made with resonance circuits and magnetic flux concentrators which improve the coupling, bringing it closer to the original transformer (Fig. 1b). As a result, the energy transfer efficiency of the two systems may be comparable in case of an appropriate design and in addition the EV on board part of the SPMS (the rectifier) has smaller dimensions and a lighter weight.



a- plug-in charger b- wireless charger

Fig. 1. Block diagrams for the chargers used in electric or hybrid vehicles

If the efficiency of the inverter and the rectifier are similar for the two charging systems, the critical area in Fig. 1b represented by the two (primary and secondary) resonators and the inductive coupler determines the wireless system performance.

2.1 Charging battery as load

The load represented in Fig. 1 is usually a variable load for the inverter, depending on the charging condition of the battery and in the case of a public charging system it depends on the capacity of the battery fitted on the EV of a particular client. For the prototype we achieved, the correct sizing of the system requires knowledge of the charging parameter specific for the type and capacity of the battery used. An important parameter is the C-Rate, which represents the rate of battery charge/discharge, by definition the numerical value of the ratio (A/Ah) between current in A and battery capacity in Ah. 1C means battery charge/discharge within 60 minutes. For Li batteries, the maximum value of C-Rate is currently 2C [4]; this means that a 60 Ah battery could be charged by 120 A in 30 minutes time. This charging condition is known as “very fast charging” which can be necessary for special applications but it is usually avoided because it leads to excessive heating of the battery and the reduction of battery life due to a decrease in the number of charge/discharge cycles. In current practice level 2C is only used to define the dynamic discharge condition of the EV battery. There are three levels for charging [1] in the range of 0.15C to 1C. For example, level 1, namely 0.15C is reached for a current of 10A and a reasonable 6 hours charging time, using a 2 kW charger, 60 Ah battery with 200 V (12 kWh) voltage. The output characteristic of a battery charger is a combination of constant power charging and constant voltage charging. Constant power charging is completed when the battery voltage reaches the cut-off-voltage [1] and is still maintained almost constant until the end of the charging process, during which the charging output power decreases 5-7 times. This type of characteristic must be taken into consideration for dimensioning the charging system with voltage and current sensors included in the inverter control loop.

2.2 Contactless battery charger

The charger presented in this paper was designed to serve the research and development of optimal constructive solutions for fitting current electric vehicles. If the theory of contactless energy transfer is well known [5], the practical achievement of these systems is characterized by a number of difficulties which will be approached next.

Design of the inductive coupler. The inductive coupler is a two-port circuit like in Fig. 2, made of two planar coils of some form (usually circular or rectangular), in air. In the most general case, the coils may be coaxial, parallel or inclined, and the distance (h) between coils may be variable (axis z), but their offset on the axes x or y is not excluded.

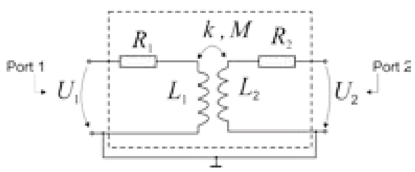


Fig. 2. Equivalent diagram of an inductive coupler

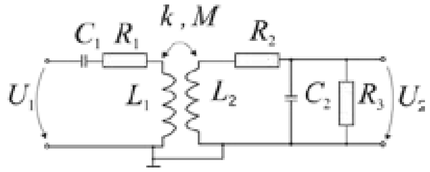


Fig. 3. Equivalent diagram of a resonant system for inductive power transfer

Therefore, the geometry of coils, their relative position, also the materials surrounding them could affect (especially in the case of EVs) the distribution of the magnetic field between coils, which determines the coupling factor k and, together with the quality factor Q of the two coils, affects the contactless power transfer efficiency. In air and at great distances between coils (20 - 150 mm), the coupling is weak (k has low values, as a rule below 0.3). For increasing the natural coupling factor, one appeals to resonant circuits in the primary and secondary of the inductive coupler [6] like in Fig. 3 where k1 > k and M1 > M.

Frequently, it is used the series resonance in primary for increasing the voltage applied to the coupler and the parallel resonance in secondary [7]. Another measure applied simultaneously with the first one consists in concentrating the magnetic flux between windings with magnetic materials of ferrite type [8].

In order to achieve a compact solution of the coupler in the EVs construction, planar coils are used almost exclusively as shown in Fig.4, located on the ground and at the bottom of the vehicle so that the ground clearance thereof would not be significantly reduced.

The sizes of the transmitter (Tx) and receiver (Rx) coils intended to this inductive coupler is able to transmit a power of minimum 2 kW under steady-state regime and 3 kW under short-time duty (5 minutes). The coils are made of Litz wire with a square cross section equivalent to 4.1 x 4.1 mm2 with 300 strands of 0.2 mm.

A method of measurement based on using a Vector Network Analyzer (VNA) described at length in [9] using the parameters defined above was developed for fast determination of inductive coupler parameters in the laboratory but also in real assembling conditions. Fig. 4 illustrates the experimental measurement conditions and Fig. 5 shows the test bench (frame dimension 1.5 x 1.5 x1.0 m) used to simulate the working conditions in operation.

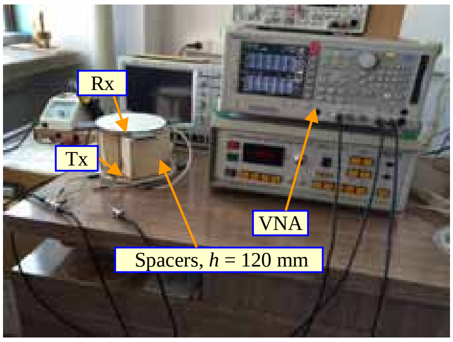


Fig. 4. Laboratory experimental set-up

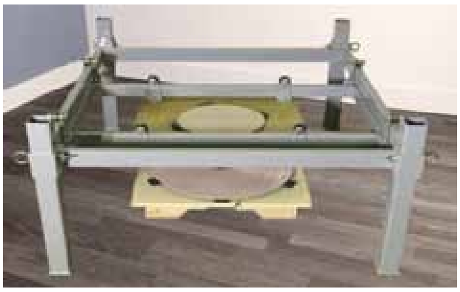


Fig. 5. Test bench (1.5 x 1.5 x 1.0 m)

Complete IPT developed System. Starting from the block diagram in Fig. 1b, Fig. 6 describes the system developed based on a multipurpose medium frequency inverter with 2/3kW output and the following features: single-phase full bridge MOSFET series resonant voltage source inverter with ZVS, phase shift or DC link regulated, frequency range: 10 - 100 kHz, automatic/manual frequency control, position detection of coils of inductive coupler, open-circuit and short-circuit protection. In addition to these protections, it controls the temperature of the coupler coils and of the MOSFET switches.

The connection with the double resonant inductive coupler type S-S or S-P is achieved through an matching transformer fitted with taps for adjustment to the load represented by the EV battery which is charged by a Schottky diodes full bridge rectifier located together with Tx coil on the EV. Using the described voltage control systems, the DC output voltage can vary between 20-300 V. The communication between the inverter and the State of Charge (SoC) is wireless. The power supply from the 230 V single phase AC source is achieved through an EMI filter to reduce the disturbance transmitted in the AC network. In addition to the disturbance transmitted, the operation of IPT systems is accompanied by radiated interference resulting from switching of power electronic circuits in the inverter and by the stray magnetic field of the inductive coupler [10], all this disturbance would have to be within the limits stipulated by ICNIRP provisions [11].

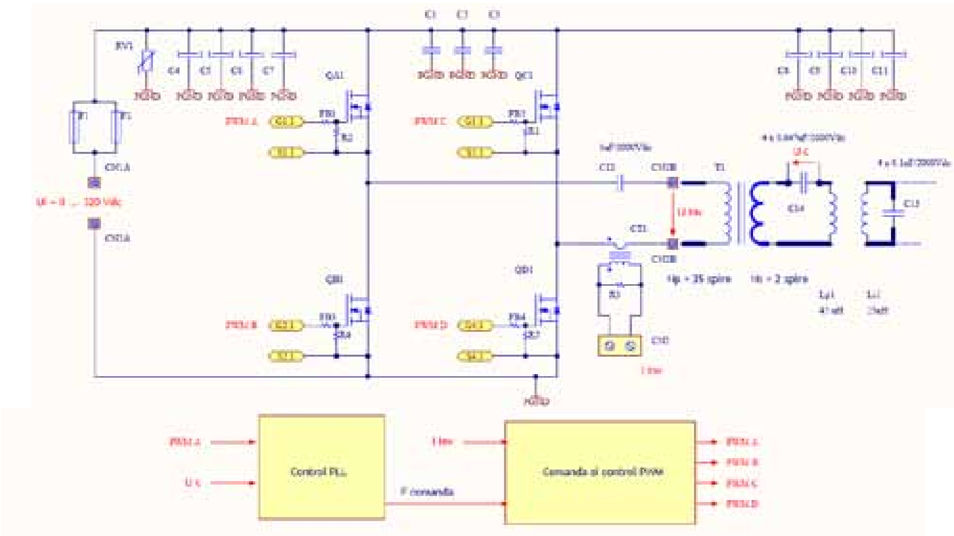


Fig. 6. Complete diagram of the IPT

Fig. 7 shows the IPT system during laboratory tests for determining the power transfer efficiency. Fig. 8 shows the components of the inductive coupler designed for mounting on the ground (Tx) and on the EV (Rx), resulting from optimization. Condensers are also fitted inside the pads to provide the primary and secondary resonance.

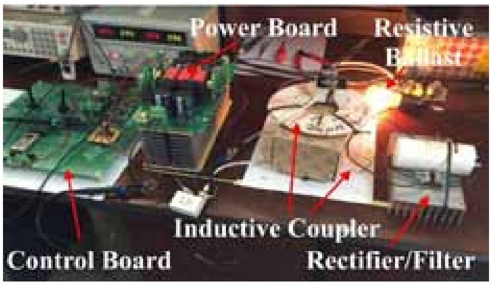


Fig. 7. Measurement set-up for power transfer efficiency

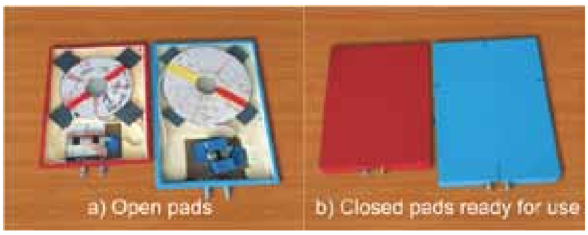


Fig. 8. Stationary Tx Pad (380 x 270 x 40 mm) and Pick-up Rx Pad (340 x 260 x 40 mm)

Comparison between the efficiency of plug-in and contactless chargers. In order to determine the energy transfer efficiency for an IPT system, the following elements must be taken into consideration: topology of resonant circuits, resonant frequency, ratio of transmit (Tx) to receive (Rx) coil dimensions, coupling factor *k* (x, y, z and angular separation of the coils), coil impedance, skin effect, parasitic elements of the coils a.s.o.

Most of these elements are optimized during the design stage of the IPT system, however, when used for charging EV batteries, the ground clearance and imperfect mutual set-up of the inductive coupler coils remain variable, both leading to the modification of the optimal coupling factor and the transfer efficiency. For this reason the operating frequency of the inverter must be modified in a certain range to compensate for a possible change in the efficiency; this action is basically carried out in an automatic control loop.

At present, the existing data in the literature [12] show that the overall efficiency of plug-in charging stations based on the SMPS (Fig. 1a) is on average 90%. Wireless systems based on the same principle (Fig. 1b) as shown in this paper, currently have an approximately 10% lower efficiency, that is of 80%, especially due to losses in the inductive coupler itself.

3 Mounting the IPT system on the Sandero Electron electric vehicle concept

3.1 Vehicle presentation

The new concept car Sandero Electron (Fig. 9) on which the IPT system is mounted, is developed this year within the Automotive Engineering Research Centre in order to achieve an electric vehicle on the mechanical platform of the Sandero Stepway II.

The electric propulsion system, called AMBRA (Amber = Electron in Greek) is built according to the current standards of components (connectors, cables, etc.) similar to those used by Duster ZERO (Zero Emission ROmanian concept) [14] and the electrical system ELECTRA that was used in different concepts of electric vehicles and hybrid vehicles: Dacia Electra- 2009 [15], Grand Hamster- 2011[16].

The new AMBRA electric powertrain is mounted of the Sandero Stepway II in the front side. It includes the following components: interconnection box, charger, traction inverter module, electric motor & gearbox, vacuum pump, and AC compressor. The liquid cooled electric motor provides a constant 18 kW and has a peak output power of 31 kW. It generates a constant torque of 90 Nm @ 2850 rpm or a peak of 160 Nm @ 1400 rpm.

3.2 The Inductive Power Transfer vehicle demonstrator for EV/PHEV

General scheme of inductive charging system is shown in Fig. 10. The system includes three parts:

- The *Mechanical assembly* and *alignment guidance coils*;

- The *Ground Transmission Unit* assembly with the primary coil and their lift system;
- The *Vehicle receiver Unit* with the Pick-up Rx Pad.

Fig. 9. AMBRA powertrain compartment

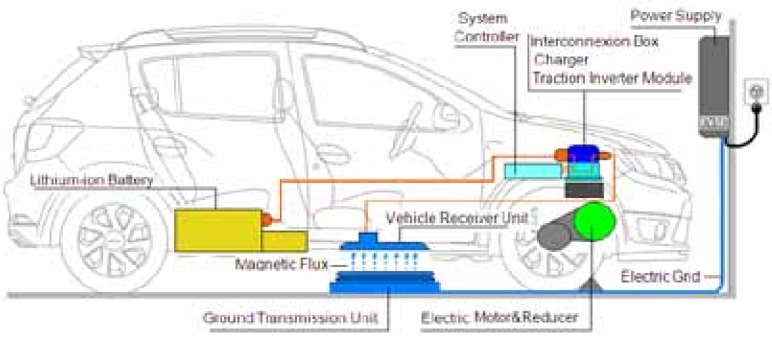


Fig. 10. The IPT demonstrator for EV/PHEV and their implementation on the *Sandero Electron* concept

With IPT, the charging energy is transferred via a floor charging pad. The demonstrator system offers a charging power of 2kW.

Prior to charging, an integrated electric motor in the floor plate raises the primary coil to improve the power transfer. The driver can interrupt the charging process. Also, the charging stops automatically when the traction battery is full.

4 Conclusions

The paper describes the first wireless charging system for an EV developed in Romania. Wireless IPT is reliable, comfortable, efficient, fast, with low maintenance cost. Now, ICMET has an infrastructure for IPT development endowed with a dedicated medium frequency 2 kW multifunctional inverter, technology and test bench for determining the coupling factor, achieving power planar coils a.s.o.

This EV prototype is used to carry out the first wireless charging station at the "Automotive Engineering" Research Centre of the University of Pitesti for the Sandero Stepway Electric Vehicle Concept.

The research and development for these systems will continue on the following topics:

- design of high power planar coils with Litz wire windings with focus on coupling and merit factors;
- shielding and packaging of transmitter/receiver units;
- efficiency improvement of resonant inverters using SiC power semiconductors [13];
- improvement of approaching, recognition and fine positioning of EV for perform power transfer;
- EMC Analysis and Design complying with ICNIRP Regulation.

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