Inductive Charging : The Automatic Approach

Prof. Dr. Ir. G. Maggetto , Ir. P. Van den Bossche, Ir. Wan Li
CITELEC – Vrije Universiteit Brussel
VUB-TW-ETEC
Pleinlaan 2
1050 Brussel
Belgium
Phone: 32-2-6293807; Fax: 32-2-6293620;
Email: citelec@etec2.vub.ac.be

Abstract

Most present day work on the charging infrastructure for electric vehicles is oriented to either conductive connection or paddle-type inductive connection of the vehicle, both of which imply the need for driver intervention. These systems may be adequate for private owners, but present a practical burden where frequent opportunity charges are performed, i.e. in applications like automatic rent-a-car systems, electric taxis, etc...

In the framework of the EVIAC ("Electric Vehicle Inductive Automatic Charging") research project, sponsored by the European Union, different topologies of inductive charging systems with automatic connection (i.e. without driver intervention apart from parking the vehicle) have been developed.

The four systems considered encompass different technologies:

- high frequency coupler using a passive mechanical alignment system
- high frequency asymmetrical coupler with active docking system
- high frequency asymmetrical couplers with high positioning tolerance
- intermediate-frequency (400 Hz) system

The systems have been implemented and tested in both laboratory conditions and real usage.

Special interest has been given to the evaluation of EMC (electromagnetical compatibility) aspects, both on the conducted and radiated level, as it has been considered that the loosely coupled inductors typical for these systems are liable to be more sensitive on the field of EMC issues.

The energy consumption and the safety aspects of the systems have been evaluated and compared to conductive systems, as to assess the operational characteristics of the inductive charging technology and their potential to be developed into a product which is both safe, technically reliable and economically feasible.

The EVIAC project is bound to be finalised in September 2000. The paper, will thus contain global information about the project, allowing the presentation of a global overview of current European research into inductive charging technology and its potential to open up the market for electric vehicles to a number of application domains where the current manual connection systems are presenting too much constraints.

Introduction

Most present day charging infrastructure for electric vehicles use conductive connection of the vehicle which implies the need for driver intervention and the use of a galvanic connection with cord or cable and plug.

Three main directions have been investigated:

- normal charging from the AC grid
- fast charging from the AC grid
- fast charging with an external charger.

These three methods are certainly adequate for the needs of the privately owned vehicle which can thus be charged on the street and at home with the same onboard charger.

For systems like automatic-rent-a-car systems, where the charging process must be totally transparent to the user for reasons of safety and user-friendliness, however, these conductive systems show some drawbacks.

In these, and other similar cases, it is necessary to develop means of charging that need no driver intervention, and are working on inductive transfer mode of energy i.e. without galvanic connection.

Electric and hybrid electric taxis or buses can equally benefit from such systems as the vehicles can be automatically charged during the waiting periods.

The systems developed may also be a precursor for urban charging systems of all types of vehicles, including the private car, freight transport vehicles and buses.

Hybrid vehicles, in so far they need to recharge separately their batteries, are also potential users of automatic charging units.

Endly, in the industrial and goods distribution worlds electric forklifts using automatic chargers could recharge their batteries on a safer way.

The objective of the EVIAC research programme is to develop the technology necessary for totally automatic inductive charging systems or stations and the associated controls required to optimise the energy usage .

Inductive charging systems on the market

Inductive charging systems rely on inductive power transfer through more or less loosely coupled inductors. The present market of inductive charging system shows two approaches which have led to industrial developments. None of these two however fully meets the specifications of the fully automatic charging system.

a Systems using mains frequency (50 Hz)

50 Hz inductive chargers are available for industrial vehicle applications.

These devices have several interesting operational aspects (energy efficiency up to 90 %, high tolerances on alignment) but are characterised by a large size and weight (about 25 kg per inductor for a 3 kW unit) which compromises their installation on lighter road vehicles.

b Systems using high frequencies are offered on the market in Japan and in the USA for power ranges up to 120 kW.

These offer exceptional power transfer capability in a small and light unit, but a plug in operation is still needed which cannot be easily automated and a connection cable is still existing.

Classification of the Inductive Couplers

The inductive couplers considered can be characterized in different ways in the family of inductive couplers.
The operating frequency and the coupling mechanism are the most important basic factors that will affect the overall system design and performances.

Based on the frequency, three subfamilies can be defined:

Low frequency	50/60 Hz, which are the typical mains frequencies.
Medium Frequency	400 Hz, which is the classical aircraft electric power frequency.
High Frequency	>20 kHz, which can be supplied by switched-mode inverters.

Based on the mechanical way of coupling the ground inductor and the vehicle inductor, the inductive couplers can be classified into three types:

Insertion type	The ground inductor is hand inserted into a port which houses the vehicle inductor; this is mainly developed in USA and Japan.
Proximity type	The ground inductor and the vehicle inductors are coupled by properly positioning the vehicle, without the help of hands nor the help of servo actuators.
Chained-Ring type	The ground inductor and the vehicle inductor are linked to each other, after positioning properly the vehicle, with the help of an actuator.

Acceptability of equipment from the city’s point of view

In order to define the needs and constraints of the city fleet users, and to fix the optimising friendliness of usage and energy management of the considered transport systems using electric vehicles, the opinion of CITELEC member cities has been evaluated through a questionnaire (47 % of them have given a response). This questionnaire deals with the following types of charging equipment:
conventional conductive
inductive charging using a high-frequency inductive connector and cable
special charging posts (n° 1 on fig. 1.)
fixed devices, flush with road surface (n°2 on fig. 1.)
fixed devices, not flush with road surface (n°3 on fig. 1.)
devices on road surface which include moving parts (n°4 on fig. 1.)
special kerb designs (n°5 on fig. 1 .)

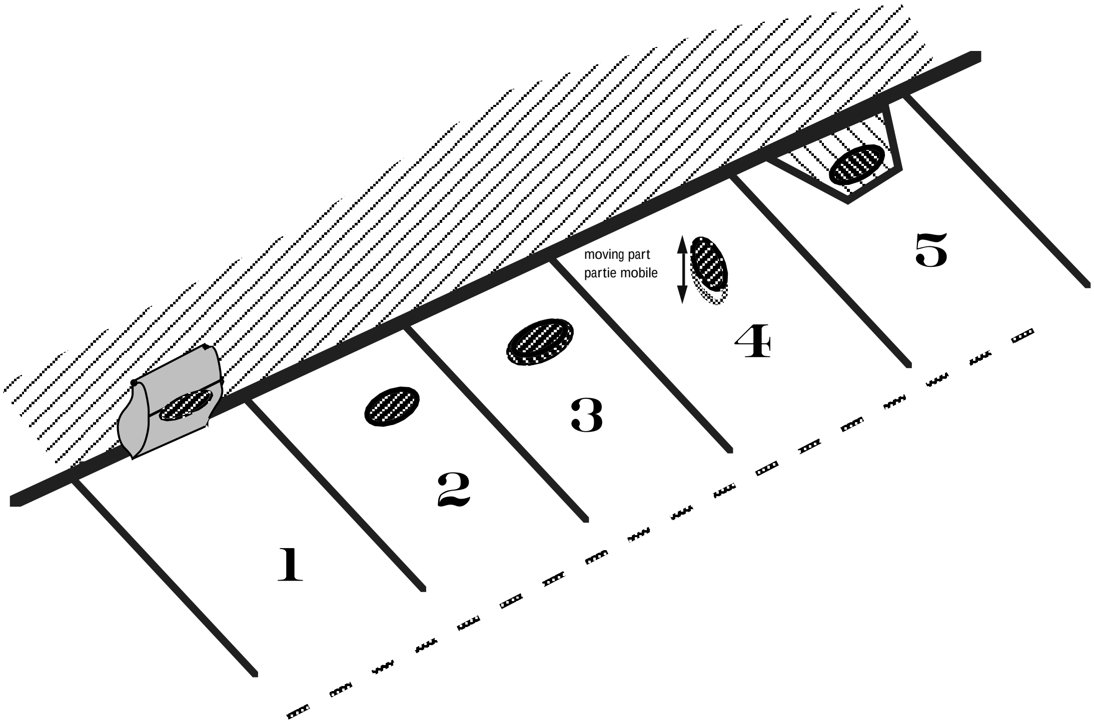


Figure 1. Inductive charging configurations
Ground side

The acceptability of equipments depends on whether the parking places for electric vehicles are located off the public highway or on the public thoroughfare.

Charging infrastructure is more tolerable off-highway than on the street. Cable-bearing devices as well as systems with moving or protruding parts are less desirable than the other three types of charging equipment.

There is a strong desirability of charging devices that **cause the smallest interference with existing road infrastructure.** That is the reason why the fixed devices, flush with the road surface is the most appreciated, followed by the special kerb designs and the special charging posts. Systems that involve the use of cables are much less appreciated.

Technical options adopted

Several types of inductive couplers are considered, according to specific requirements of the application.

Charger with passive mechanical alignment

Mechanical aspects

The problem of inductive recharging is how to set up a situation in which the inductive transmitter and receiver are facing one another. When parking takes place without mechanical guidance, the positioning of the vehicle is uncertain. There is no guarantee that the receiver and the transmitter are opposite one another. The mechanical system will therefore need to compensate for the uncertain positioning, by offering a degree of latitude in final adjustment.

The automated induction recharging system developed by Electricité de France's Research Department has been designed for incorporation into a Renault Clio electric vehicle. The work with Renault covered the incorporation of the charging system into the Clio, in all its mechanical and electrical aspects.

Two alternative solutions belonging to the proximity type were possible for the prototype mechanism :

Either fixed component on ground, and mobile component on underside of car,

Or mobile component on ground, and fixed component on underside of car.

The second solution was agreed.

The alignment mechanism comprises:

ground mobile component integrated into the guidance block,

underbody fixed component (guidance plate, guidance skid and inductive receiver).

This mechanism ensures the precise alignment of the inductive transmitter to the receiver fixed on to the vehicle underbody.

Electrical aspects

The vehicle is a RENAULT passenger vehicle, the electric Clio.

It is equipped with a 114 V battery, and an on-board charger, which under normal circumstances is connected to the 230 V alternating current network for recharging purposes. This equipment uses the battery load curve to manage the whole charging procedure.

The Clio's on-board charger was not modified for this application. It can therefore operate either on the 230V single phase network, or as an output from the inductive coupler. When the charger operates with the voltage from the inductive coupler, the rectifier at the input stage of the charger is shunted. The inductive coupler has therefore been designed to give an output voltage equivalent to the rectified 230V.

Figure 2 presents the overall architecture of vehicle battery recharging, when operating on the output from the inductive coupler.

The on-board computer manages remote recharging for a vehicle fleet.

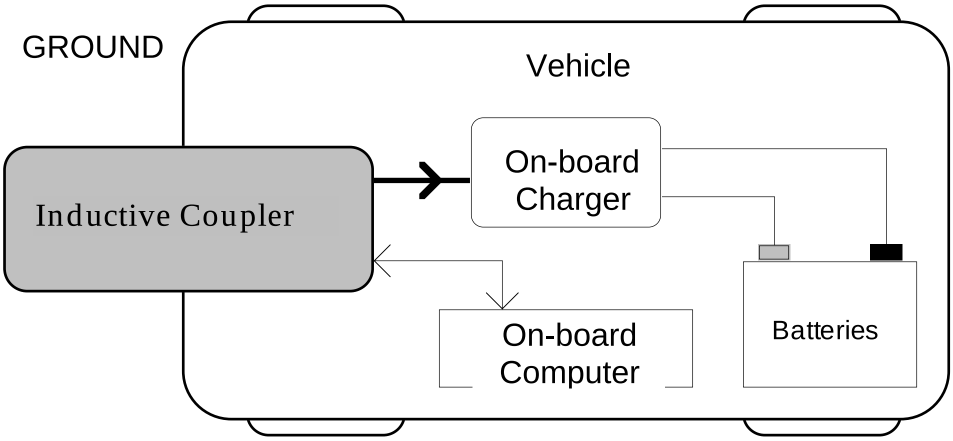


Figure 2 : Functional interface of recharging equipment with vehicle

Communication aspects

The self-service concept means that we have specified a "user transparent" recharging approach. Battery recharging should be automatic, once the vehicle is stationed in the recharging location. Automatic recharging constraints, as well as the constraints of contact-free recharging, require a high-performance communication system between the vehicle and the recharging infrastructure.

Understanding of the communications involved in the system requires a proper grasp of the differences between the two operating modes of the induction recharging system, namely:
"manual" mode
"automatic" mode

The automatic mode is particularly well suited to the management of a fleet of electric vehicles, which requires a number of stations equipped with inductive recharging terminals. In this case, fleet management is centralised at a control station common to all recharging stations. Vehicle recharging is controlled from the central control station, and commands are sent to the on-board computer of the relevant vehicles. The recharging instruction takes into consideration a number of criteria, such as off-peak power supply management, number of vehicles available on station, levels of charge, etc. The on-board computer then sends the recharging command to the inductive coupler located on the vehicle. This in turn sends the recharging instruction to the ground inductive transmitter.

Manual mode: the manual mode was developed for the first stage of the induction recharging system validation. Recharging is manually controlled by an operator actuating a dummy "Marechal" connector. Connection to the vehicle actuates a relay in the Clio, making it possible to send the vehicle recharging command to the ground infrastructure.

Asymmetrical charger

The main reason for considering this structure is to get simultaneously good coupling quality and a structure allowing easily automatic positioning. The structure is shown in figure-3. It belongs to the chained-ring type family.

Figure 3 Ground casing (underpart)
Moving core in “closed” position

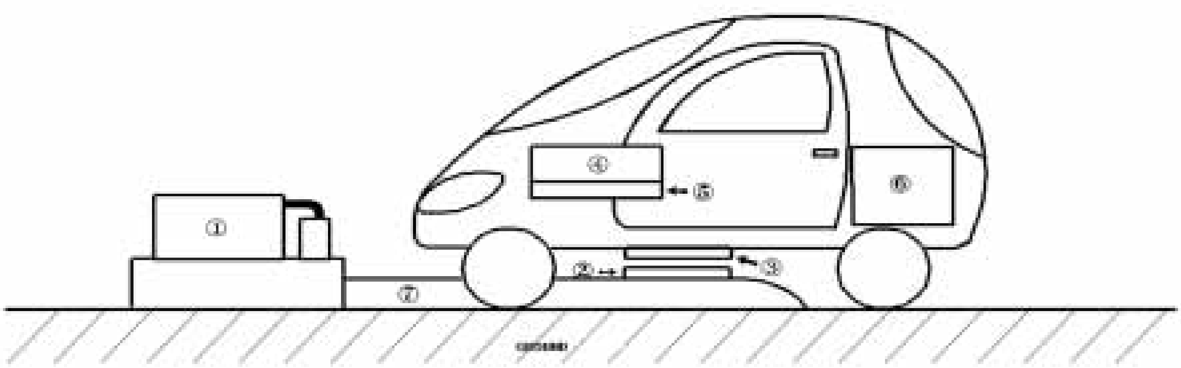
The core is composed of two parts, a fixed part and a movable part. The movement can be a rotation or a translation. The last one has been chosen. The primary winding is closely wound on the fixed part of the core. The secondary winding forms a movable ring (the copper ring). The ring can be mounted on the vehicle integrated in the bumper or protected by the bumper. When the copper ring is chained to the core, the two parts of the core form a ring too (iron ring). When the copper ring is moved away the iron ring is open and its moving part is in the position ready to be chained again.

Asymmetrical large air-gap charger

The third system developed is an experimental high frequency high tolerance asymmetrical system belonging to the proximity type family.

This system uses a coil that can be imbedded in the roadway. It is therefore totally non obtrusive. The reception coils are larger than the transmission coils and accept very large parking errors without resorting to mechanical alignment, from there rsukts the so-called asymmetrical characteristic. This system is particularly well adapted to roadside parallel parking.

This system is shown on fig.4



① Outboard charger: primary system ② Primary coil: inductor ③ Secondary coil
④ & ⑤ Onboard charger: secondary system ⑥ Battery ⑦ Wheels guide sidewalk

Figure 4. Large air-gap charger

The communication between the primary system and the secondary system is realised by a transistor in the onboard charger which short-circuited the resonant circuit, so the power transmission. The primary system detected this power's variation and switches his current's orders.
The efficiency of this system is constant when the air gap varies from 30 to 60 mm.

Alternative Medium-Frequency coupling system

The fourth system developed is an intermediate-frequency (400 Hz) system.

This system retains some interesting features of the mains-frequency systems while considerably reducing weight and size. It can be integrated with 400 Hz generating equipment which is an industry standard.

The inductive coupler is based on a conical shape to allow for the docking accuracy along the vertical and horizontal axes as shown in figure 5.

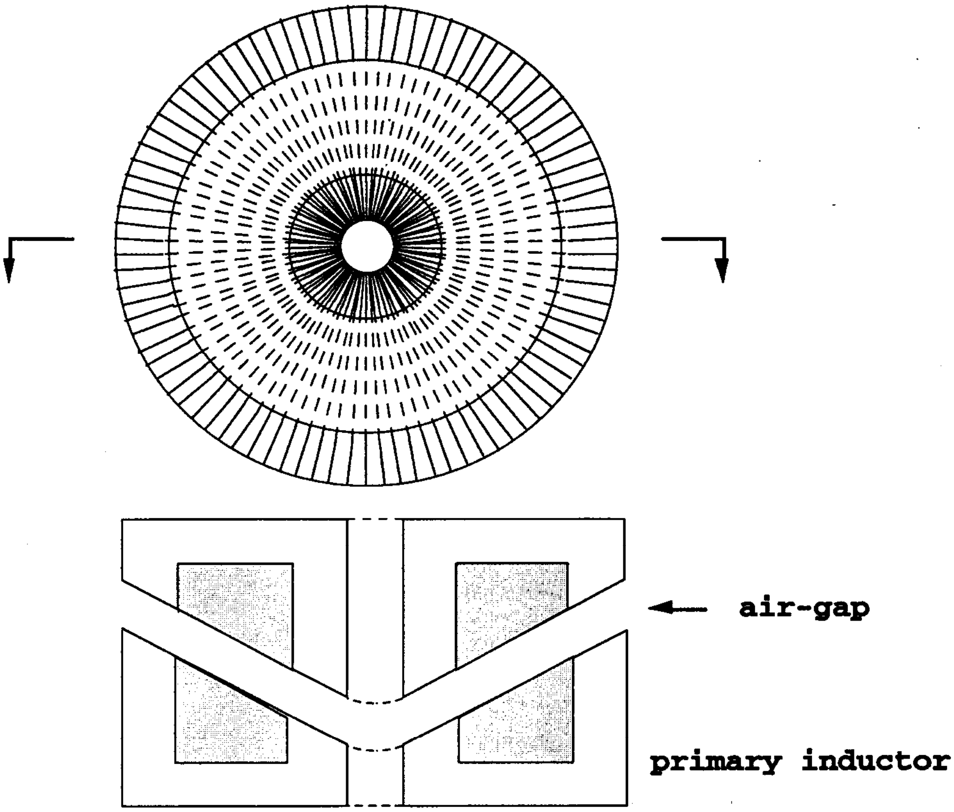


Fig. 5 : Structure of the 400 Hz pot-core coupler

The coupler is excited by a load resonant converter operating in the frequency range of 400 to 600 Hz. The conical shape also offers the possibilities of minimising the magnetising current through the choice the cone angle.

Control loop

For the control loop a communication system s necessary between the car, i.e. the battery, and the ground structure, i.e. the primary coil and the associated resonant converter performing the power covnersion from the AC mains; this structure us similar for all types of inductive charger discussed in this paper.
This can be realised by an IR or RF communication link.
Fig. 6 shows the principle structure of the control loop.

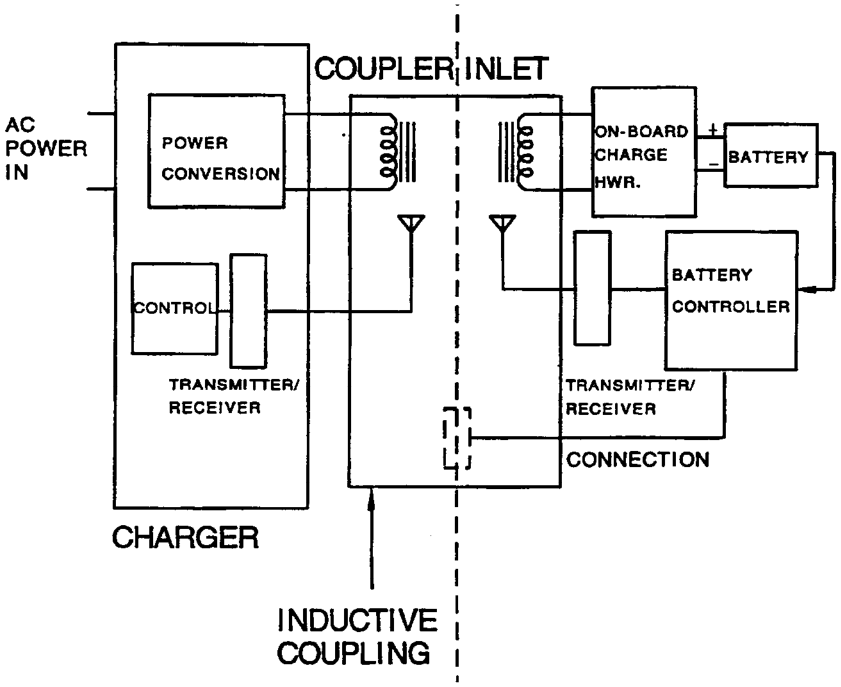


Fig. 6 : General aspect of inductive charging system

-A board computer can control the charging procedure of the battery.In this case the secondary voltage and current are measured and sent to the base station by RS232 and handled on an adhoc way.
-In an other structure, a voltage and current measuring PCB with microcontoller and RF link is foreseen in order to allow testing the charger system as a stand alone system.

EMC tests plan

The tests are being performed as laboratory tests on prototypes, laboratory tests with the device installed on-board vehicles and in-situ (parking station) measurements.
The table I, which includes all the applicable immunity tests, the basic standard for the test procedure and the levels of the disturbances according to the generic EMC standard has been used as test programme.

The performed tests can be characterised as follows :

The aim of the test is to verify that the battery chargers comply with the requirements of the European Directive 89/336 for EMC aspects. In particular the goal to point is the immunity to the disturbances as defined in the generic standard for industrial environments (an environment more severe than the residential for an adequate immunity margin). For the emission aspects the more severe limits of the residential environment has been considered applicable.

Three criteria has been defined for the classification of the test results in order to make easy the comparison of the device of each partner. The criteria, which are in line with those defined in the generic standard, are summarised here and reported in detail in the test plan:

Criterion A: No effects.
Criterion B: The Equipment Under Test (EUT) shall continue to operate as intended after the application of the disturbance.
Criterion C: Permanent failures or manual interventions are needed in order to restore the normal operations of the EUT.
The battery charger were operated in normal conditions during the immunity tests. The battery voltage and the charging current have been monitored in order to apply the proper criteria for the result. For the emission measurements the “worst case” condition have been searched.

The tests listed in the table have been applied to the whole system installed on board vehicles.

The “in-situ” (parking station) measurements have been mainly devoted to verify the emission aspects (conducted and radiated) during the charging phase of several vehicles.

Concerning the magnetic field it has been decided to measure, both in the laboratory and “in situ” tests, the emissions, according to the CISPR procedure. The measurement results have been analysed and considered as information and not as requirements.

Most of the tests have been performed successfully and indicate the applicability of all systems.

IMMUNITY					
Test	Disturbances	Basic IEC/CENELEC	Test plan	CE mark(IND)	
• Enclosure port					
1.1	Power frequency magnetic field	IEC 61000-4-8	30A/m cont. 300A/m 1s	30 A/m	
1.2	RF electromagnetic field	IEC 61000-4-3 + Amd. 1	10 V/m	10 V/m	
1.4	Electrostatic discharge	IEC 61000-4-2 + Amd 1	6 kV conct. 8 kV air	4 kV cont. 8 kV air	
30- Signal and control port (**if any**)					
2.1	Surge	IEC 61000-4-5	1 kV	1 kV	
2.2	Electrical fast transient	IEC 61000-4-4	2 kV	1 kV	
2.3	Conducted disturbances induced by RF fields	IEC 61000-4-6	10 V	10 V	
3) a.c. power supply port					
3.1	Harmonics and interharmonics	IEC 61000-4-13 (draft)	See doc.	Not include..	
3.2	Voltage dips	IEC 61000-4-11	30% 1 per 60% 50 per.	30% 0,5 per. 60% 5 per. 50 per.	
3.3	Voltage interruptions		100% 5-250 per.	>95% 250 per.	
3.4	Slow voltage variations		+12% / -15%	not include..	
3.5	Electrical fast transient	IEC 61000-4-4	2 kV	2 kV	
3.6	Surge	IEC 1000-4-5	2 kV	2 kV	
3.7	Conducted disturbances induced by RF fields	IEC 61000-4-6	10 V	10 V	
Earth port (**if any**)					
4.1	Electrical fast transient	IEC 1000-4-4	2 kV	1 kV	
4.2	Conducted disturbances induced by RF fields	IEC 61000-4-6	10 V	10 V	

EMISSION					
Meas.	Disturbances	Basic IEC/CISPR	Test plan	CE mark (RES)	
1	L.F. harmonics and interharmonics	IEC 61000-3-2	Class A	EN 60555-2	
2	L.F. Voltage fluctuations	IEC 61000-3-3	dc< 3% dmax 4% Pst = 1	EN 60555-3	
3	R.F. Conducted (0,15 – 30 MHz)	CISPR 22	66-56-60 dB(µV)	66-56-60 dB(µV)	
4	R.F. Radiated (30 – 3000 MHz) (10 m dist.)	CISPR 22	30-37 dB(µV/m)	30-37 dB(µV/m)	
5	Magnetic field	CISPR 16 - ….			

Table I: EMC testing

Comparison between the different types

What follows gives elements of comparison guiding the choice in function of the applications.

Positioning and alignment requirements.

Compared to the other types of couplers, the insertion type needs a strict alignment of the inductors onboard the vehicle. It lends itself difficulty to an automatic positioning by an auxiliary device and needs to be inserted manually. Because the ground inductor is connected to the ground station with a flexible cable and hand-inserted into the vehicle inductor, there is no special requirement for the vehicle positioning.

The disc-shaped proximity type coupler tolerates some millimetres misalignment between the inductors. However, because the alignment of the coupler is done by drive-on, the requirement for the vehicle positioning is strict. The vehicle must be guided and blocked by auxiliary devices.

The chained-ring type coupler tolerates much more misalignment between the inductors. More important, there can be a flexible compromise between the coupling parameters and the margin of misalignment. The vehicle positioning margin can be designed to fit the statistical vehicle positioning behaviour (refer to [3] for detail). To avoid failure and damaging hit, simple measure should be taken to help the vehicle positioning. The coupling of the inductors is no more accomplished by a single drive-on movement like what happens with the proximity type. It is a two-stage movement: first the vehicle is positioned and then the vehicle inductor is chained to the iron-ring by a rotating actuator.

The positioning and alignment characteristics of different types of coupler are summarised in table-II.

table-II summary of the positioning requirements

type	vehicle positioning	inductor alignment
insertion	tolerant	strict, manually,
proximity	strict, auxiliary help,	medium tolerant hand free
chained-ring	medium tolerant auxiliary help	tolerant, actuator hand free

Performances

High frequency inductive couplers are working in conjunction with electronic power converters. The performances of the whole system should be evaluated at the end-to-end scale. But some of the system performances are inherently determined (or limited) by the inductive couplers.

The system power efficiency is influenced by each stage of the system. The inductive coupler, besides its own losses causes some losses elsewhere in the system. The magnetising current, for instance, contributes for a part of the reactive power in the resonant loop which causes power losses (refer to [8] for detail).

The insertion type coupler produces the lowest losses within itself because of the compact structure and shows the lowest magnetising power because of the highest coupling coefficient.

The disc -shaped proximity type coupler produces higher copper losses because of the spreading of its windings and needs higher magnetising power because of its lower coupling coefficient.

The chained-ring type coupler produces higher losses in the secondary winding and the core because of the length of respectively copper or magnetic loops but needs medium magnetising power because of its coupling characteristics.

The power transfer capacity is inherently limited by the inductive coupler. But there is no clear cut relation between the parameters and the peak power that the coupler can transfer. The system design is a compromise within the design space determined by the components, and operational parameters and constrained by various specifications. Generally speaking, when the coupling quality is becoming worse, the design space is shrinking. The decreased peak power capacity is one of the results of the compromise within the shrunken design space.

The power capacity of the three types, resulting from the possible values of their parameters, can be relatively classified as high, medium to high and low for the insertion, chained-ring and proximity types respectively. The disc-shaped proximity type differs from the other types by the dependence of the coupling quality on the volt per turn (V/T) value. For example, a single turn secondary winding is possible for the insertion and chained-ring types, but not for the proximity type.

Thermal constraints can play a key role which limits the power capacity of the inductive couplers. The insertion type, because of the most compact structure, has the worst natural cooling condition. The chained-ring type, on the contrary, has the best natural cooling condition because of its loosely structure.

Regarding the EMC, the situation is just opposite to the thermal condition. The structure of the insertion type is compact and magnetically closed, thus the EMC is the easiest to be controlled. The structure of the chained-ring type is loosely and magnetically exposed, thus the EMC is the most difficult to be controlled.

The performances of different types of coupler are listed in table-III for a quick comparison.

table-III summary of the performances of the inductive couplers

type	power rate	power efficiency	thermal condition	EMC
insertion	high	high	bad	good
proximity	low	medium	medium	medium
chained-ring	medium to high	medium to high	good	bad to medium

Conclusions

Introducing a user-friendly charging system for EV/HEV reduces the resistance of the citizen to accept it and helps introcuding in the city ZEV systems able to reduce the number of vehicles in the city and to improve the mobility.

Inductive charging system can become a key element of charging infrastructure in the cities.

Automatic-Rent-a-Car systems are an intermediate step between classic public transportation system and private cars. It is a prolongement of public transport that splits the latter into possibilities for local trips not coverable by public means.

It should be financed in the same way public transportation systems are financed.

With respect to costs: the maintenance costs are very similar to the costs of classic electric material; the energy costs are related to the benefit (more or less 50%) connected with the introduction of EV's.

For all other applications - buses, taxis, fleets – the infrastructure is very similar to parking meters infrastructure i.e. with similar investments and maintenance costs.

The environmental advantages of inductive charging systems are strongly related with the advantages of introducing electric and hybrid transport systems in cities.

They do not introduce particular urban problems considering the easy integration they allow.

The choice of the exact inductive technology to be selected will be mostly dependent on the particular requirements of each system application.

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