Charging Infrastructure for Electric and Hybrid Electric Vehicles

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1. Introduction

Electric vehicles are an important factor for improving the traffic in urban areas and creating a healthier environment. It is a dream for the human being, city traffic without exhausting gas and low noise. This is already partly realised by trams, undergrounds and railways and other recently developed automatic and lightrail systems (e.g. airport shuttles). But cars, vans, buses and lorries are route independent vehicles for low and high speed, for city traffic and long distances; consequently energy must be stored on board.
We are quite rapidly reaching the end of the cheap oil era. This could happen around 2010 and is nowadays probably indicated by the steadily growing oil price. Therefore the need for alternative energy source is growing and the price competition of alternatives against oil is becoming more and more realistic.
Electric and electric hybrid vehicles are offering the best possibility for the use of new energy sources, because electricity can result from a transformation with high efficiency of these sources and is always used with the highest possible efficiency in systems with electric drives or components. The main parts of an electric vehicle were invented in the last century. The car body was adapted from a coach powered by horses. The electric parts: battery, motor and controller were also used for general purpose and the mechanical transmission with gear, shaft or chain were used also in common machinery applications. Today's technology includes modern motor design influenced by power electronics and automotive views, energy sources performing better and better to match acceptable vehicle performances and performant control and data acquisition.

The electric vehicle needs an infrastructure to allow the charging of its batteries.
For small and medium sized vehicles, the typical power needed for charging in 8 hours (normal charging overnight) is 3 kW. A standard 220 V, 16 A outlet is able to deliver this power.
Such a power could also easily be made available on public places. In countries like France, Germany, Switzerland, the United Kingdom and Finland on-street charging stations have been developed. The cost of the energy used during charging is much lower than normal downtown parking fees.

The development of on-street charging infrastructure must be done with a particular emphasis on safety aspects and standardisation.

Inductive charging systems have been proposed as an alternative to the conventional conductive systems.

The inductive charger is a very user-friendly and safe system which will contribute to promote the use of electric vehicles in urban traffic thanks to its efficiency and simplicity.

The inductive technique may have some very obvious advantages:

- there is no conductive coupling, no plugs or sockets, and less danger of electrocution
- the coupling can be automated, eliminating driver intervention and enhancing user comfort.

In this paper, several technological solutions to provide inductive charging, and the practical realisations in the field, are illustrated.

2. Electric vehicle charging modes

The electric road vehicle may be used for different missions and charged in different conditions; to this effect, several modes of charging have been defined.

- Mode 1 charging: the direct connection of the electric vehicle to the existing AC supply network utilising standardised socket outlets/connectors and associated plugs, of domestic or industrial type, rated up to the usual voltage of 220/380 V normally used for supplying electrical equipment other than electric vehicles, with no additional electrical safety figures incorporated into the ac supply of the socket, and provided that all conditions are appropriate for that purpose (e.g. indoor plugs and sockets must only be used in suitable indoor conditions).

  Mode 1 charging uses existing supply infrastructure and is mainly aimed to the charging of electric vehicles in domestic premises, allowing the vehicle owner to charge at home without having to install special equipment.

- Mode 2 charging: the direct connection of the electric vehicle to the AC supply network using dedicated electric vehicle supply equipment.

  This is in fact the mode of charging which will be applicable for on-street electric vehicle charging stations.

  The design of unique charging sockets and plugs for electric vehicles for mode 2 is under consideration; some of these materials, like the “French unified charging cable”, present design features and dimensions which make them compatible with mode 1 plugs and sockets.

  In view of the developments with fast charging using a direct AC coupling (cf. the UK system proposed above), a special mode 2 may be defined using high power AC connections up to 125 A rated current.

- Mode 3 charging: the indirect connection of the electric vehicle to the AC supply network using an off-board charger and a DC link.

3. Basic charger configurations: conductive charging

Basic charger configurations

Electric vehicles are largely independent of the charging place if they are equipped with an on-board charger connectable with any AC outlet. A 230V/16A outlet can supply an apparent power of more than 3.5kVA. Such an outlet can be installed everywhere, in public parkings, in home garages,.... A battery of 15kWh can be charged in less than five hours (main charging) with a charger having a unity power factor.

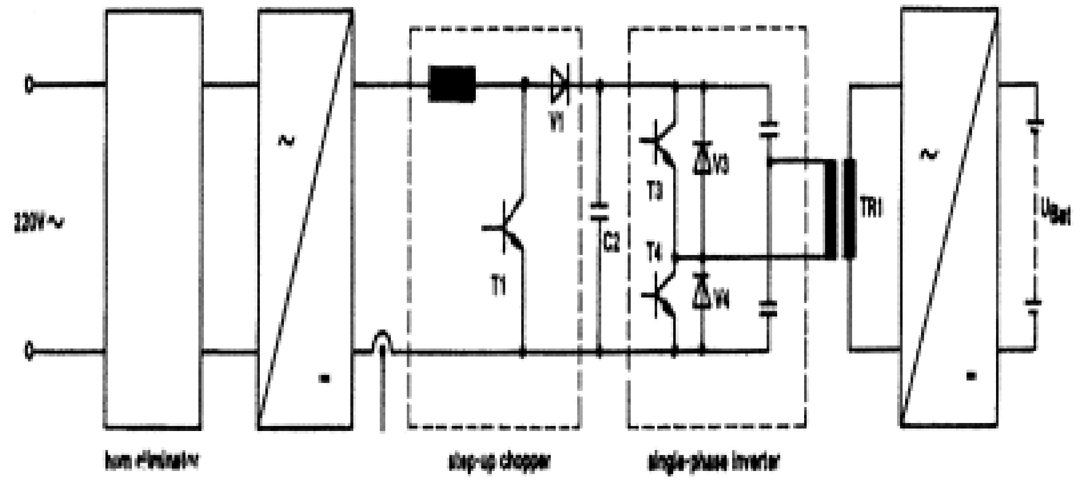


Fig. 1: Basic circuit diagram of a charger

Electric utilities in Europe are nowadays demanding more and more consumers with low distortion and reactive power requirements. From the AC power supply system a quasi sinusoidal current with a low harmonic content, at unity power factor, can be obtained only by means of a step-up chopper. Fig. 1 shows the basic circuit diagram of the charger. The advantages of resonant converter (RC) and quasi-resonant converter (QRC) are mainly the small switching losses. The switching frequency can be increased compared with the conventional PWM converters even by using the same switches. The snubber circuits are not necessary in RC and QRC .

In Europe, three-phase feeding is used for powers higher than 3.5kW. This is a line normally separated from the usual AC single-phase distribution. The DC link voltage is obtained from a three-phase uncontrolled diode rectifier bridge and gets a maximum voltage of 540V. The DC-DC converter must control the battery voltage. Depending on the connection to the AC grid, this system can also be used as off-board charger. Off-board chargers for higher powers are not limited in space and weight. Thus, a conventional controlled rectifier with a 50Hz transformer can be used efficiently. High power is disposable in Europe from the AC three-phase 400V grid. The controlled rectifier is mostly a six-pulse bridge. The protection against insulation faults can be made on different ways .

Looking at the configuration of an inverter for AC-Motor drive, Fig. 2, it is clear

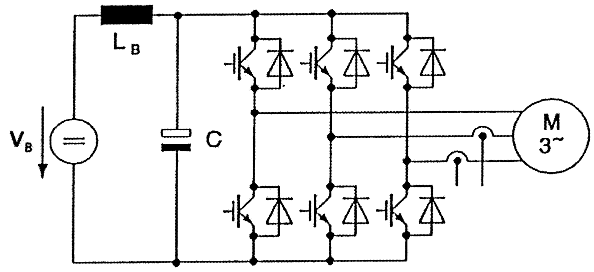


Fig. 2 Inverter for AC Motor

that the reversibility of the inverter allows its use as a charger for the battery. This solution makes the ground part of the charging path lighter.

4. The need for public charging stations

Even considering that, like stated above, most electric vehicles can be charged at home garages, the provision of public charging stations may be a necessity, for the following reasons:

- Some users, particularly in densely built urban areas, do not have a private garage available. They must rely on street-side parking or on public car parks.
- The availability of public charging stations may be an interesting point taking into account the possibility of opportunity charging.
  Today's electric vehicles are mostly able to cover distances of 100 km or more on a single charge. Daily covered distances for urban vehicle users are often only half of this or even less. However, in some cases an extra long distance might be covered in one day, and in these cases the availability of opportunity charging may be an interesting option. Moreover, the knowledge of the fact that extra charging is available "wherever" will greatly enhance the confidence of the user in the electric vehicle and in its ability to cover his or her transportation needs.
- The highly visible implantation of electric vehicle charging infrastructure on public roads greatly enhances the awareness of the public concerning this infrastructure and the environmental image of the city concerned.

For this reason, electric vehicle charging infrastructure is being implanted on the public road by a number of local authorities interested in electric vehicles.

5. Examples of public charging stations in European cities

In this paragraph, some of the most characteristic examples of sites where public electric vehicle charging infrastructure is installed will be described. The focus will be on infrastructures which are available for the general electric vehicle driver, i.e. not on infrastructures which are aimed at captive fleets like automatic rent-a-car systems or which are located on private premises.

France

The most developed infrastructures are present in France, which may be considered the leading nation in the field of electric vehicle deployment in Europe nowadays.

In the coastal city of **La Rochelle**, the foremost pilot town for electric vehicles, recharging stations have been deployed in the framework of the well-known local electric vehicle demonstration programme. Ten normal charging stations, Fig. 3, have been installed in seven different areas in the town and three rapid stations are located in petrol stations, Fig. 4.

Fig. 3 : Normal charging station at La Rochelle

The rapid stations are designed for emergency recharging and provide about 20 km driving for 10 minutes charging. Electricity consumption is charged to the user, who accesses to the system using a smart card. The rates at the rapid charging station are substantially higher than at the normal stations (FRF 13.5/h peak and FRF 8.10/h off-peak, against FRF 2.25 and FRF 1.35 in the normal stations).

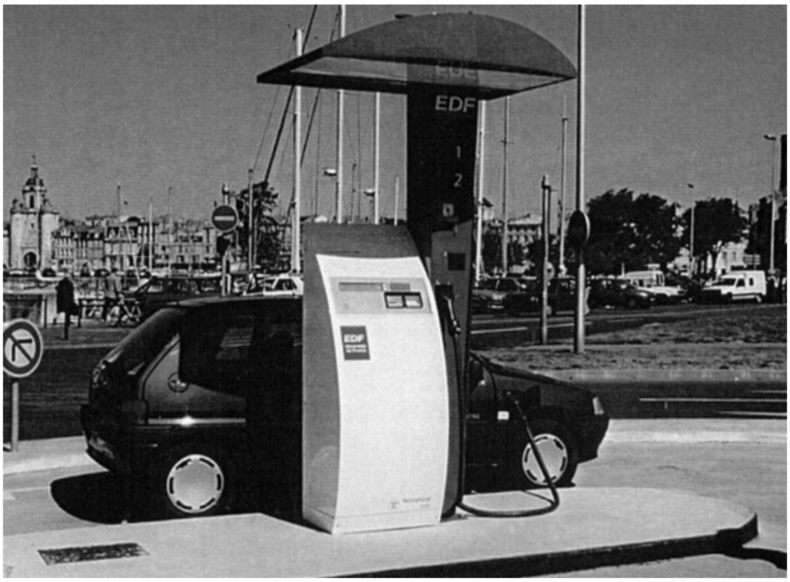
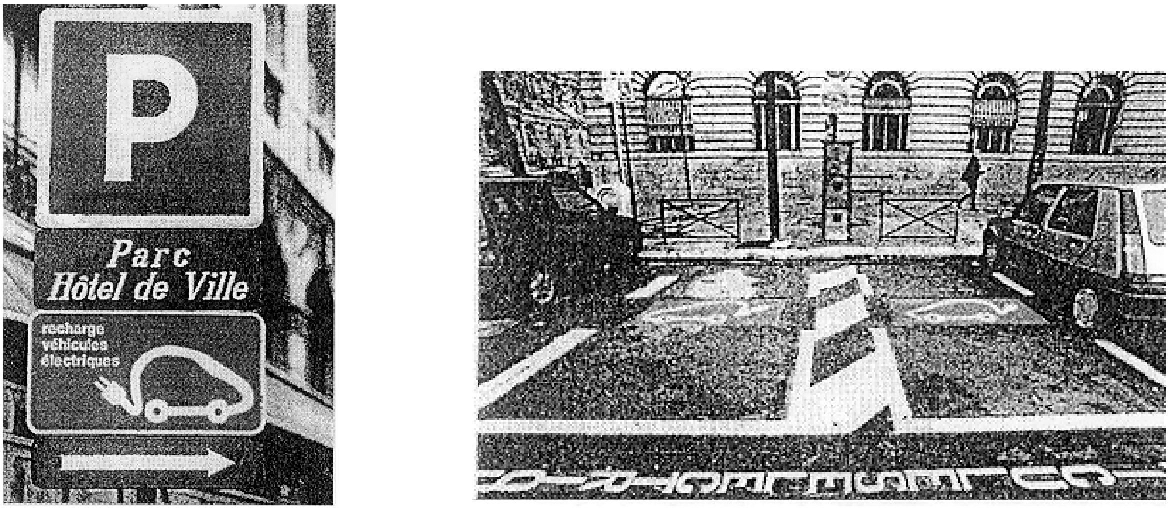


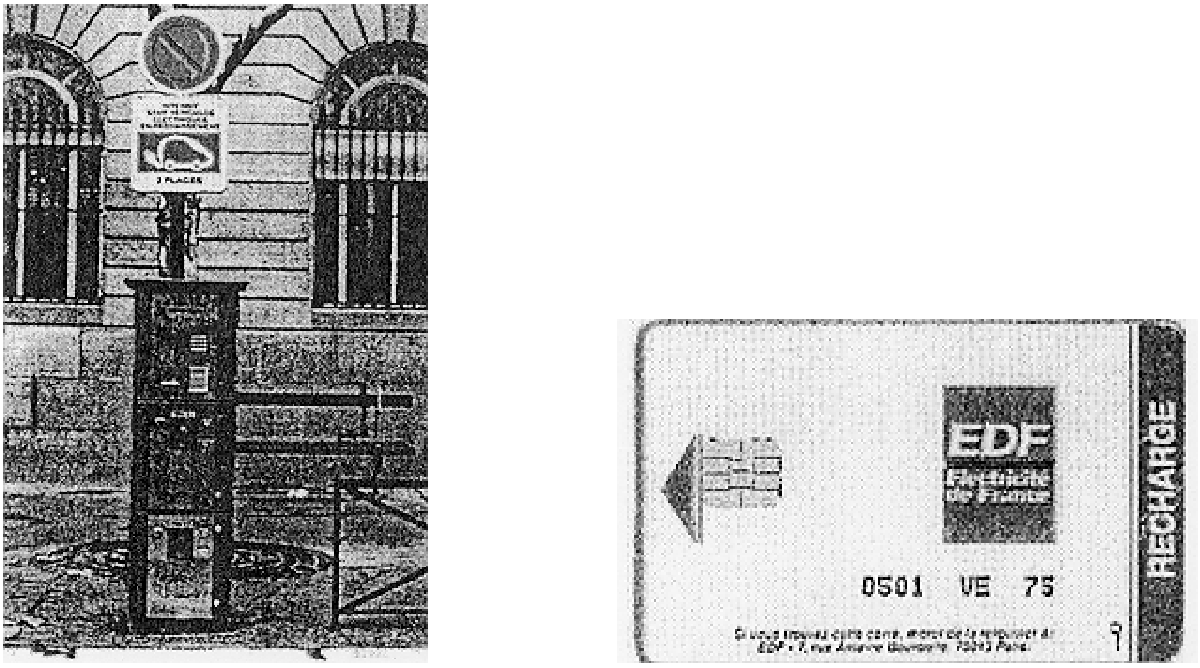
Fig. 4 : Fast charging station at La Rochelle

Paris, the French capital, has also developed a quite extensive network of charging facilities. Nowadays, not less than 122 parking lots which are reserved for electric vehicles and equipped with charging facilities are available. Eighty charging points are available, distributed over eight underground car parks.



Parking sign

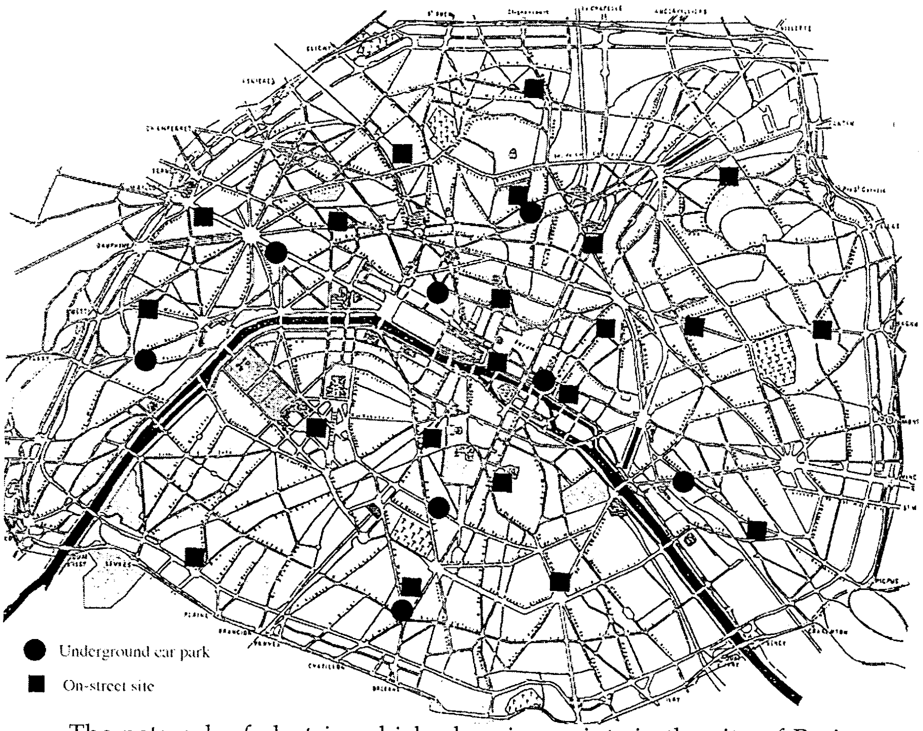
Parking places



Charging base

Smart card

Fig. 5 : Details of charging infrastructure



The network of electric vehicle charging points in the city of Paris

Fig. 6 :

Forty-two charging sites are deployed on the streets. These kerbside sites are fitted with charging posts allowing the charging of two vehicles.
Access to the system and payment is done through smart-cards which are distributed by EDF (Electricité de France), Fig. 5.

Germany

A number of facilities have also been developed in **Germany**. In many cases, these are associated with solar energy generating facilities. The renewable aspect of solar energy does in fact appeal quite a lot to the public opinion in Germany.

Fig. 7 : A “Solar” charging station at Erlangen, Germany

In a typical “solar” charging point, an 1100 W solar array, Fig. 7, is located on the roof of the adjacent building, and is connected on the grid through a suitable inverter. Electric vehicles can come and charge at the charging post; the electricity grid is used as a buffer.

Switzerland

In **Switzerland**, a dedicated infrastructure under the label "Park&Charge" is developed by the ECS (Electromobile Club of Switzerland), with the support of the electricity producers (UCS). A number of charging posts with three, Fig. 8, to six outlets each are now active; extensions is continuous. The pilot city of Mendrisio alone has ten charging points, the capital Bern has seven; the system has been implanted in many other cities.

Access to the system is reserved to electric vehicle owners, who have to subscribe to the system and pay a modest yearly subscription. They obtain a vignette to affix to their windscreen, and receive a physical key giving access to the charging posts.

Energy is billed through the purchase of "energy cards", which have to be marked with the day of usage. There is a lump sum for energy consumption per day of usage, according to the weight class of the vehicles.

The operators of these "Park&Charge" charging posts can be public or private bodies.

The operator has to buy the charging posts; electricity consumption is billed through to the "Park&Charge" organisation, which pays the consumption from its income from the sale of "energy cards".

Fig. 8 : A three charging outlets column in Switzerland

Optionally, an operator may decide to offer its electricity free of charge. This saves the installation of a separate energy meter and may thus give an advantage. In this case, the use of the "energy cards" is not required.

The system has been under test in Bern since more than 4 years. The main experiences gained can be summarised as follows:

- the usage of the charging stations is dependent on their location; city centre facilities are the most popular;
- the energy consumptions are modest: about 2 kWh per outlet per day;
- the charging at the Park&Charge represents only about 20% of total charge, the rest being charged at home;
- no incidents have taken place.

United Kingdom

A particular type of charging station is being prepared in the **United Kingdom** by the electricity producer **Powergen** with an experimental facility proposed for Coventry. The particularity of this concept is that it uses on-board fast charging, unlike other fast charging stations which rely on an off-board charger and a DC link.

The on-board fast charge can be performed using the traction controller to rectify the AC from the grid; this technique will be particularly interesting for vehicles fitted with AC drives. (The British example is using "Wavedriver" technology.) This leads to an infrastructure cost which, at about 6000 EURO per 25 kVA charging point, is claimed to be 10 times lower than for an off-board fast charging approach.

The same controller can also, of course, be used for ordinary (slow) charging, fast charging being offered as an option.

Possible applications for this system are short stay car parks such as found at shopping centre and supermarkets, where the availability of high power charging can also be useful for the recharging needs of commercial delivery vehicles.

The AC connection with the grid will of course be of a higher power level: 63 or 125 A instead of 16 A.

Northern Europe

The Finnish city of **Hameenlinna** also has established a charging station which is installed at a city centre car park.

In **Stavanger**, Norway, a multi-storey car park in the city centre has been provided with power outlets for electric vehicle charging, in a joint action by the car park operator and the electricity company.

The electric energy is provided free of charge, furthermore, the parking fee is waived for electric vehicles as a step to the promotion of this environmentally friendly transport.

In Nordic countries, a distribution infrastructure for electricity in car parks is widely present for the use in engine pre-heaters. This infrastructure is generally quite basic, but it could be easily adapted for electric vehicle charging purposes.

6. Standardisation of electric vehicle charging : conductive charging

The wholesale introduction of electric vehicles and their acceptance by members of the public will lead to a situation which is unique with no historical precedent: a high-power connection (3 kW for normal charging, up to 25 kW or more for fast charging), made daily, in outdoor conditions, by members of the general public which are not electrically trained. One may think that the public has learned to live with electricity which has been our major source of energy for over 100 years now, and such power levels are quite common in household installations, but the conditions of use here are quite different:

- connections of high powered electrical devices (washing machines, water heaters, cookers, ovens....) are made only once when the machine is installed, often by a qualified electrician; electrical vehicles however are daily on the move;
- the use of electrical equipment in outdoor, all-weather conditions is normally not performed in an ordinary household environment;
- potential electric vehicle drivers, which are members of the general public, including specific groups such as elderly people, disabled people and mothers with small children, usually have not received a specific training about dealing with high power electrical equipment; the idea alone of "high electric power" may actually frighten them off from electric vehicles.

The connection of the electric vehicle to the charging network must be performed with a very high level of safety and reliability in order to gain acceptance by the public. In normal conditions the energy transfer between the supply network and the vehicle shall be operating safely, causing no danger to persons or surroundings, even in the event of carelessness that may occur in normal use.

Furthermore, the introduction of public charging infrastructure, in order to be economically viable, must be able to accommodate a wide range of different vehicles; the vehicles themselves, in order to obtain a sufficiently high operational flexibility, must be able to use as much different kinds of charging infrastructure.

Hence there is a need for specific standardisation of electric vehicle charging.

6.1 General requirements for the conductive charging system

Since the energy stored in the traction battery provides the power for electric vehicles, such vehicles require a method of charging their battery on a regular basis. Conductive charging is a method of connecting the electric power supply network to the vehicle for the purpose of transferring energy to charge the battery and operate other vehicle electrical systems while connected. The most widely used method of connecting electrical sources and loads consists of electrical contacts that join the electrical conductors at the vehicle/supply interface. Conductive couplings allow an open architecture for the charging system design and the location of the primary components. The primary method for electric vehicle charging is to extend the AC power supply to an on-board charger as the means of charging at power levels similar to common large appliances in homes at a constant average voltage and constant frequency of 50 Hz. For the special case of charging an electric vehicle at special charging facilities, or for fast charging at high power levels, an off-board charger will be utilised delivering direct current.

6.2 Electric vehicle requirements

The electric vehicle shall be connected to the AC electric vehicle supply equipment so that in normal conditions the charging function operates safely, indoors or outdoors, causing no danger to persons or surroundings, even in the

event of carelessness that may occur in normal use.
This principle is achieved by fulfilling relevant requirements, and compliance is checked by carrying out relevant tests.

The requirements proposed are focused on electrical safety: protection against electric shock, dielectric strength, ...

Electromagnetic compatibility is considered particularly important; both the immunity against external disturbances and the generated electromagnetic disturbances are treated. Lack of immunity against electromagnetic disturbances may in fact have consequences on other electric vehicle equipment.

As to improve functional safety, a drive train interlock is required. The use of the vehicle shall be inhibited until the vehicle is properly disconnected. The vehicle shall be able to detect the presence of the connector. and / or socket-outlet, and, where applicable, shall verify if the cable is correctly stowed.

The proposed standards will include other general safety and functional statements: permissible temperatures, mechanical latching to prevent abuse, impact resistance, markings required,....

6.3 Charging station requirements

An AC electric vehicle charging station is defined as a device for delivering alternative current to electric vehicles, installed under the same enclosure. An AC electric vehicle charging station may be electric vehicle supply equipment or part of it.
If several AC supply points are necessary, it may be economically interesting to gather some functions (e.g. payment) under the same AC electric vehicle charging station, of important current rating, associated with individual AC electric vehicle charging stations, with one or two supply points.
The AC electric vehicle charging station shall be connected to the electric vehicle so that in normal conditions the charging function operates safely, indoors or outdoors, causing no danger to persons or surroundings, even in the event of carelessness that may occur in normal use.
In general, this principle is achieved by fulfilling the relevant requirements specified in the standard and compliance is checked by carrying out all relevant tests.
The requirements proposed are focused on electrical safety: protection against electric shock, dielectric strength,...

Electromagnetic compatibility is considered particularly important; both the immunity against external disturbances and the generated electromagnetic disturbances are treated.

The proposed standard will include other general safety and functional statements: permissible temperatures, mechanical latching to prevent abuse, impact resistance, markings required,....

7. Inductive charging

Electric vehicle inductive charging compared to the traditional conductive charging system has the advantage of safety, durability and convenience.

The safety of the inductive system has two aspects. Firstly the vehicle is electrically isolated from the mains and secondly there is no part of the electric conductors being exposed to the atmosphere; there is no contact risk. The inductive coupler, being either of the hand inserted type or of the proximity type, is more durable than the conductive coupler composed of a plug and a socket.

The durability results from the elimination of any conductive contact under pressure.

The convenience regarding vehicle charging is a very important aspect of users friendlyness; it results from the simplification of the connection procedure.

Because of the limited energy storage, opportunity charging at good chosen timing is recommended to extend the total daily range of the vehicles. This means that the handling to be done by the drivers to charge the batteries, if occuring frequently, must be as easy and safe as locking and unlocking a door. With inductive coupling it is possible to make the charging fully automatic.

Furthermore, the inductive system can easily be adapted for wide ranges of charging power and battery voltage levels. Compared to a classical on-board charger, the on-board power stage of an inductive system (on-board inductor and rectifier) can be more cost effectively built for wide power range.

The key stage of the inductive system is **the inductive power coupler,** which differentiates the system from any other power conversion systems. This paper is based on a series of laboratory experiments and provides a discussion on the inductive couplers for EV inductive charging systems. Most attention is given to the couplers suitable for an automatic handling.

7.1 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.
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.

7.2 Discussion on the couplers at different operating frequency

The choice of the operating frequency will affect almost all the aspects of the system. These aspects include the way of mechanical positioning, the configuration of the charging control, the limit on the power level and others.

7.3 Low Frequency Inductive Coupler

Inductran is the only EV inductive charging system that works at mains-frequency (1,2). The analysis of a full range of applications of the Inductran system has been completed at the end of 1994 [3] Based on the experience and the results out of this project, comments on the mains-frequency inductive coupler are given hereafter.

At the frequency of 50/60 Hz, it is not realistic to consider either the insertion type or the chained-ring type of couplers. The inductors are not suitable to be positioned manually or by actuators because of their heavy weight and large volume. The proximity type is the proper choice. At 3 kW rated power, each inductor weights 30 kg, Fig. 9.

Because of the big air-gap of the proximity type, the coupling quality of the coupler is generally bad. To get acceptable coupling quality, measure has to be taken to enlarge the cross section of the fluxpath. In the Inductran the pole surface area of the inductors is designed ten times as large as the effective core section area. Fig. 10 sketches the inductors' structure. This special structure leads to extra weight and volume. The coupling coefficient can serve as criterium to evaluate the coupling quality. The coupling coefficient k for different air-gap lengths is given in table 1.

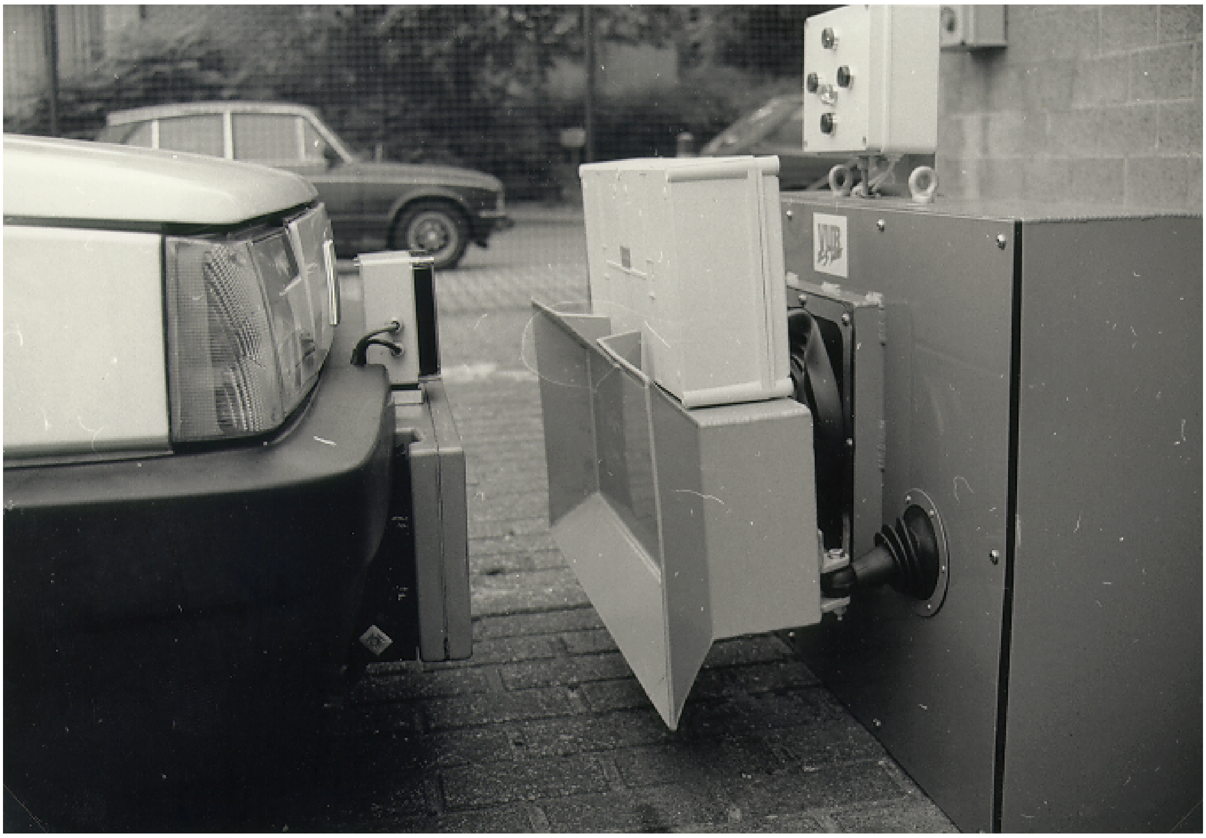


Fig. 9 : VUB-Davis Derby – CITELEC kerbside charger with a vehicle approaching

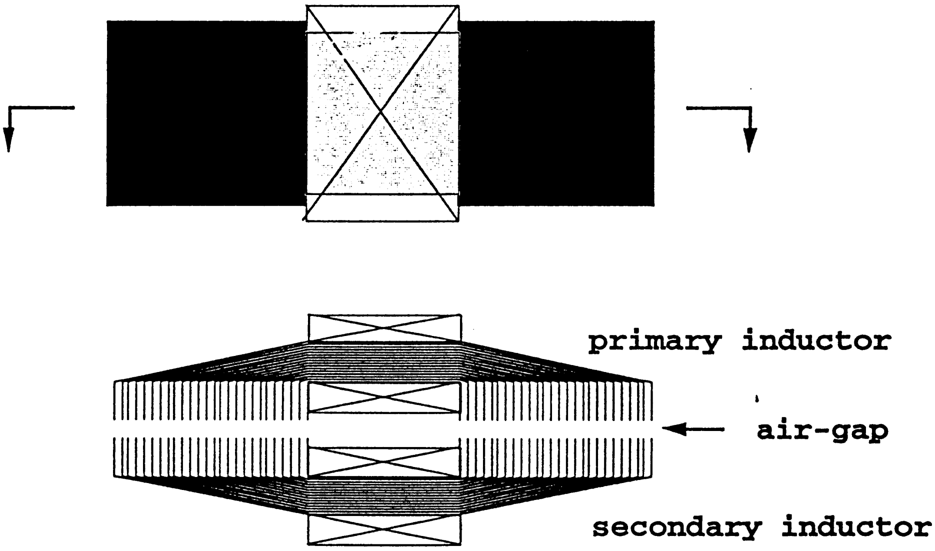


Fig. 10 : Structure of the Inductran inductive couple

Table-1 k vs. air-gap (Inductran)

Air-gap	k
1 mm	0.94
5 mm	0.89
10 mm	0.83
15 mm	0.77
20 mm	0.73

A non-metallic frame is necessary to enclose and protect the metallic parts of the inductors. Consequently the air-gap can not be smaller than6 - 8 mm. Finally, the effective air-gap will be between 10 and 20 mm. The nominal air-gap for a 3 kW set is 16 mm and the coupling coefficient is about 0.75. The simple way to control the output voltage of a system including such a transformer is the ferro-resonant Constant Voltage Transformer working mode also called (CVT).

Generally, a CVT performs two functions:
-within a variation window of the primary voltage it keeps the secondary voltage nearly constant;
-its output impedance is low until a certain power level; for the use as battery charger two supplementary aspects have to be taken into consideration: the insensitivity to the variation of the length of the air-gap and to the misalignment margin;
-the typical load characteristics of a battery charging sequence.
This leads to a quite critical setting of the magnetising curve, the turns ratio and the value of the ferro-resonant capacitance.

Summarizing, a low frequency inductive coupler controlled in a ferro-resonant configuration has the following features:

-the configuration is simple and hence the system is reliable, cost effective and suitable for hard environment;

-with passive regulation, it cannot fit the various charging regimes which are required by the various battery types;

-the cumbersome inductors, the acoustic and electromagnetic noise make the system not very compatible with a passenger car and public charging sites;

-it is quite difficult to increase the power rate above 3 kW in applications for lightweight vehicles because of the weight of the part on board.

Considering these features, it is clear that the system finds its best application in industrial environment e.g. for charging the battery of electric forklifts.

7.4 Medium Frequency Inductive Coupler, 400 Hz

The motivation to consider 400 Hz is twofold, on the one side, the achievable reduction of weight and volume, on the other side the existence of this frequency for generators and converters in the aeronautics. 400 HZ is a limit frequency for the use of classical iron cores. This reduction of weight and volume leads to more choices for structure design and to much easier integration of the inductor into the vehicle. This is discussed in WP4.

With exactly the same shape as the 50 Hz Inductran, the linear dimension of the 400 Hz coupler will be reduced by a factor 0.6 i.e. the size of the pole surfaces will be reduced by a factor 0.36. Due to the fact that the stray effect of the air-gap depends on the ratio between the pole area and the air-gap length, the allowable dimension of the air-gap is also reduced by a factor 0.36. The weight will be reduced to one fifth.

The structure of a conical pot-core design is shown in Fig. 11. A forecast of the coupling quality of the pot-core coupler is given in table-2 referring to the coupling coefficient k.

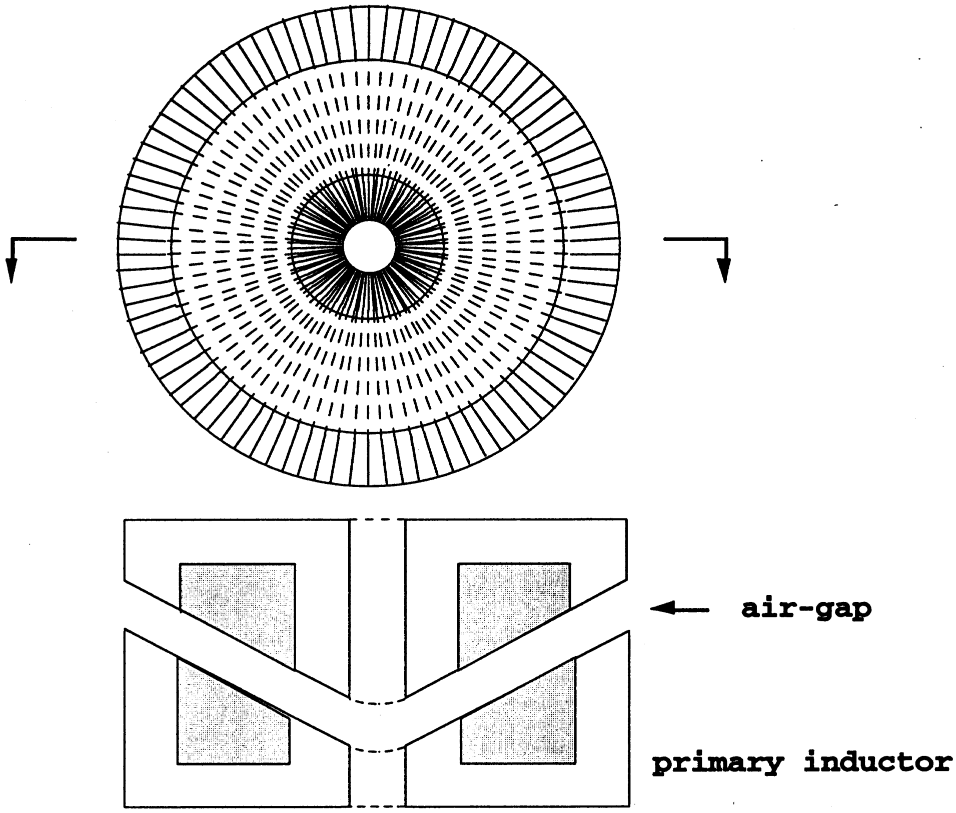


Fig. 11 : Structure of the 400 Hz pot-core coupler

Table-2 k vs. air-gap (400 Hz pot-core)

air-gap	k
1 mm	0.84
3 mm	0.79
6 mm	0.72
9 mm	0.66

The optimal design of the 400 Hz system depends on its location on board the vehicle. The proximity type is preferable. The ferro-resonant control working mode is no more possible ant the choice will be a power transfer control with PWM or resonant converter.

7.5 High Frequency Inductive Couplers (>20kHz)

The high frequency switching-mode conversion technique enables the use of high frequency inductive couplers. When an inductive coupler is connected with a resonant converter, its leakage inductance becomes (a part of) the resonant inductance.

At frequencies from 20 kHz to some hundreds kHz, weight and volume of the inductive coupler are more dependent from the requirements on factors like coupling quality, positioning, thermal condition and mechanical or electrical strengths rather than decisively dependent from the electromagnetic design. From another point of view, because at high frequency the weight and volume of the inductors are strongly reduced they become much easier to handle and there is more choice for the structure design. As listed in § 7.1, all positioning types become practical for high frequency couplers; they all use resonant converters which are introduced hereafter.

7.5.1 The resonant converters (RCS)

This category is referring to the so-called conventional resonant converters. The main configurations include series loaded series resonant converter (SRC) and parallel-loaded series resonant converter (PRC). Regarding the operation mechanism they are the most basic systems and, following author's opinion, the most robust against the variation of the resonant parameters. The SRCs and PRCs are controlled by frequency modulation (FM) instead of PWM. When the switching frequency is above the resonance, the switches turn-on under ZVS condition. When the switching frequency is below the resonance, the switches turn-off under ZCS condition. When the SRCs and PRCs are operating in discontinuous current mode, ZCS occurs at both turn-on and turn-off.

Both SRC and PRC have the option of using an isolating transformer whereby the resonant capacitor can be put at the primary or the secondary side of the transformer. When the leakage inductance of the transformer is to be included in the resonant inductance, the secondary resonance becomes a must for the PRCs.

Further, it is possible to distinguish Quasi-Resonant Converters (QRCs) and Multi-Resonant Converters (MRCs) but as they are not convenient for our application they will not be discussed.

The resonant converters are not sensitive to the leakage inductance of the transformer but they are sensitive to the magnetising inductance of the transformer if the magnetising current is significant compared to the resonant current. Therefore, problems arise when the inductive couplers are connected to resonant supplies. While there is merely very limited technical information released on existing commercial systems such as the Hughes systems, etc., even less theoretical investigation has ever been reported on this subject, i.e., the impact on the operation of the resonant converters of the introduction of loosely coupled inductive couplers.
Furthermore, the reasons why the SRCs have been chosen are now analyzed.

1. Resonant converters (SRC and PRC) have the highest power transfer capability.

2. The operation of the resonant converters (SRC and PRC) are more robust against variations in the resonant parameters compared to the other types of the categories.

3. The SRC is preferable to the PRC in this application background. When the magnetising inductance of the coupler is considerably decreased, the topologies with secondary resonant capacitor for both SRC and PRC will loose the merits of ZCS. Moreover, if the primary side is thought as a server device and the secondary side is thought as an user device, the primary should be as less as possible dependent from the secondary to be a more universal server. From this point of view, the primary resonance topology is better than the secondary resonance topology. If we choose the topology of primary resonance, PRC must be excluded because its resonant topology does not absorb the leakage inductance into the resonant inductance and this is not acceptable in the case of low coupling quality.

4. The SRC is the most widely applied topology. Thus a corresponding deepest understanding would be more appreciated.

7.5.2 The Circuit Model of the SRC

The conceptual circuit of a series-loaded resonant DC-DC converter is drawn in Fig. 12, where the marked components and parameters are respectively:

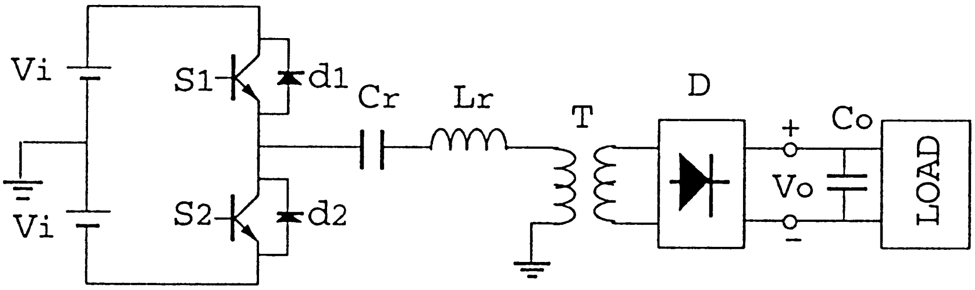


Fig. 12 : Series resonant DC-DC converter

vi	input voltage source,	D	output rectifier,

S1, S2	transistors,	C0	output filtering capacitance,
d1, d2	diodes,	V0	output voltage
Cr	resonant capacitance,		
Lr	resonant inductance,		
T	coupling transformer,coupled inductors,		

7.5.3 Parameters and Performances.

Beside the coupling coefficient k, there are some other parameters which are important when an inductive coupler is operating in conjunction with a resonant converter. Fig. 13 gives the equivalent circuit model of the coupled inductors to help defining the parameters. All the circuit parameters are refered to the primary side.

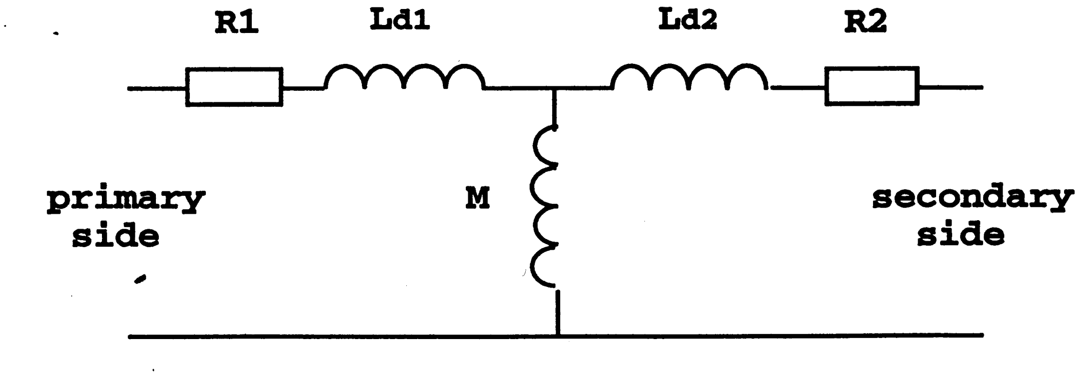


Fig. 13 : Circuit model of an inductive coupler

From the equivalent circuit of Fig. 13 the following parameters can be defined.

Mutual inductance	M	(1)
Total primary inductance	$L_1 = L_{d1} + M$	(2)
Total secondary inductance	$L_2 = L_{d2} + M$	(3)
Coupling coefficient	$k = M / \sqrt{L_1 L_2}$	(4)
Symmetry coefficient	$d = \sqrt{L_1 / L_2}$	(5)
Secondary short circuit inductance	$L_{s1} = L_{d1} + L_{d2} \; // M$	(6)
Primary short circuit inductance	$L_{s2} = L_{d2} + L_{d1} \; // M$	(7)
Damping resistance	$R = R_1 + R_2$	(8)

When the coupler is connected to a resonant converter, for instance a series resonant converter, the above parameters will affect the system steady-state characteristics in the following way.

a. Resonant frequency ω_o

$$\omega_o = 1/\sqrt{C_r L_r} \qquad (9)$$

Lr is the resonant inductance. *Cr* is the resonant capacitance which offers a freedom for setting ω_o..

If the configuration is "primary resonant" and there is no extra added inductance, then

$$L_r = L_{s1} \qquad (10)$$

or

$$L_r = L_{d1} + L_{d2} \qquad if\ M >> L_{d2} \qquad (11)$$

If the configuration is "secondary resonant" and there is no extra added inductance, then

$$L_r = L_{s2} \qquad (12)$$

or

$$L_r = L_{d1} + L_{d2} \qquad if\ M >> L_{d1} \qquad (13)$$

b. Characteristic impedance Z_o

$$Z_o = \omega_o L_r \qquad (14)$$

c. Power base and maximum power

The power base is

$$P_{base} = V_i^2 / Z_o \qquad (15)$$

where Vi is the input voltage. The maximum output power Pmax can be expressed as

$$Pmax = \varepsilon(k, Q)P_{base} \qquad (16)$$

where ε is a real number which is function of the coupling coefficient k and the resonant quality factor Q which is defined as:

$$Q = Z_o / R \qquad (17)$$

d. Power factor and power efficiency

The power factor of the converter, under the assumption of lossless operation and steady-state condition, is defined as:

PF = output power / (output power + circulating power) or $$PF = P_O / (P_O + P_{cir}) \tag{18}$$

In continuous current operational mode the power factor of the series resonant converter is

$$PF = dkq\mu, \tag{19}$$

where d is given by (5), k is given by (4), q is the conversion ratio and $0<\mu<1$ is a variable representing the effect of the magnetising power which is a part of the total virtual power [8].

The power efficiency cannot be explicitly expressed with the above parameters. The impact of the inductive coupler on the power efficiency appears via two ways. The first is the power factor and the second is the current waveform factor. In the continuous current mode the power factor is the dominant way via which the coupling quality affects the power efficiency.

Table-3 summarises the relationship between the parameters and the performances. The left-hand column contains the parameters of the inductive coupler; the middle column contains the attributes of the resonant conversion system and the right hand column contains the system performances.

$$\begin{bmatrix} L_{d1} \\ L_{d2} \\ R_1 \\ R_2 \\ M \end{bmatrix} \quad \begin{bmatrix} \omega_o \\ Z_o \\ P_{base} \\ k \\ Q \\ \varepsilon \\ \mu \end{bmatrix} \quad \begin{bmatrix} P_{\max} \\ PF \end{bmatrix}$$

Table-3 Parameters and Performances

7.5.4 Structures and parameters of different types of inductive coupler

a. Insertion type

The insertion type inductive coupler is represented by the Magne-Charge which is developed by Hughes Aircraft Company. The inductive coupler of the Magne-Charge is described in detail by the document SAE J-1773 [5]. The principle structure is shown in Fig. 14 and the typical values of the electromagnetic parameters are listed in table-4.

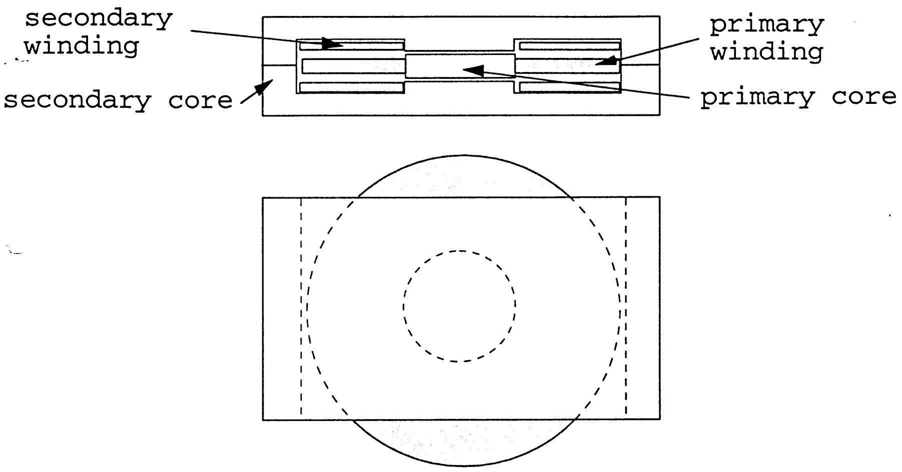


Fig. 14 : Structure of the Magne-Charger inductive coupler

table-4 parameters of the Magne-Charge inductive coupler

R_1	L_{d1}	M	R_2	L_{d2}	k	d	V/turn
30mΩ	0.65μH	50μH	30mΩ	0.65μH	0.987	1	100

† The resistance are the values at the frequency 100k<f<350kHz.
†† All the secondary parameters have been reduced to the primary.

b. Proximity type

The proximity types of high frequency inductive coupler are represented by the ones used in the inductive charging systems of Tulip [6] and Praxitele [7]. The principle structure of the Tulip inductive coupler is given in Fig. 15 and the one of Praxitele is given in Fig. 16. In the same way as we mentioned in section 7.3 for the low frequency inductive coupler, the proximity type coupler needs inductors with large coupling surface. Looking at these two couplers, the large coupling surface is achieved by the disk-shaped design. The large winding surface plays a more important role than the iron pole surface as it is the case with Inductran. Such a design with a large number and diameter of turns is inevitably accompanied by large leakage inductance and copper resistance. Measurements have been carried out on a pair of similar inductors in order to establish a comparative basis for the chained-ring type. The structure of the tested inductors is like what is shown in Fig. 15 and Fig. 16. The diameter of the inductors is 17 cm and the turns number is 12:12. The results of the test are given in table-5.
The values for k and d are to be considered for a first step of comparison purpose only.

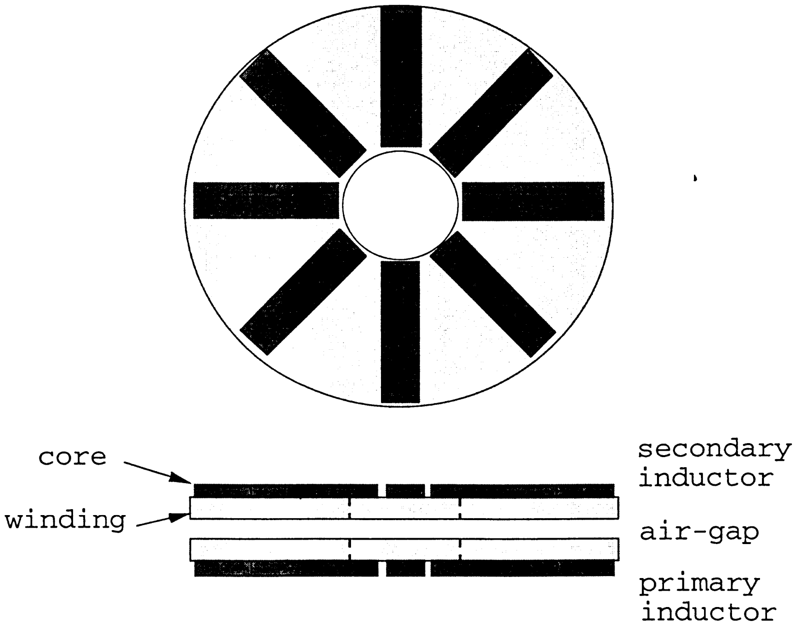


Fig. 15 : The structure of the Tulip inductive coupler

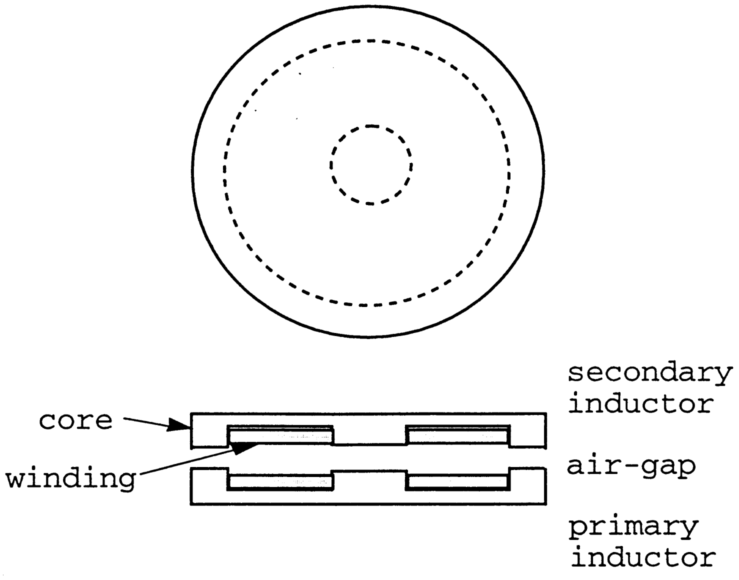
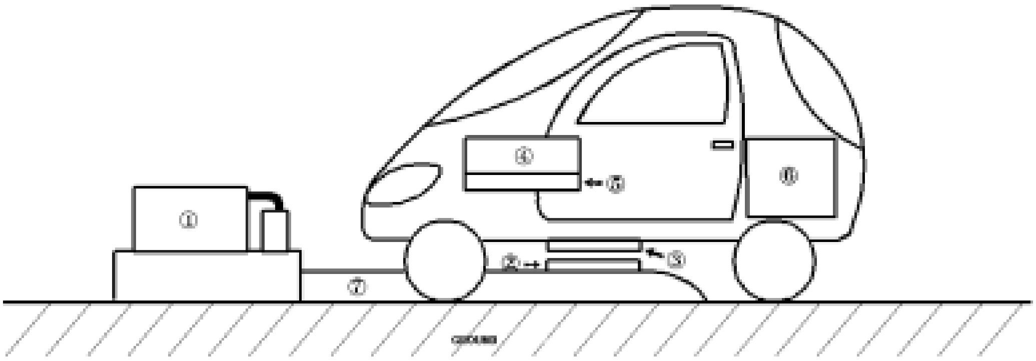


Fig. 16 : The structure of the Praxitele inductive coupler

Fig. 17 shows the relative localisation of the ground part and on board the vehicle part of the inductive coupler.



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

Fig. 17 : Relative position of proximity type of HF inductive coupler

Table-5 parameters of the disc-type inductive coupler

Air-gap	R_1	L_{d1}	M	R_2	L_{d2}	k	d
1 mm	24mΩ	38μH	158μH	24mΩ	38μH	0.806	1
3mm	24mΩ	41μH	123μH	24mΩ	41μH	0.750	1
6mm	24mΩ	43μH	96μH	24mΩ	43μH	0.691	1

† The resistance are calculated dc value with 590/φ0.09 litz wire.
†† All the secondary parameters have been reduced to the primary.

c. Chained-Ring type

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 Fig. 18. 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.

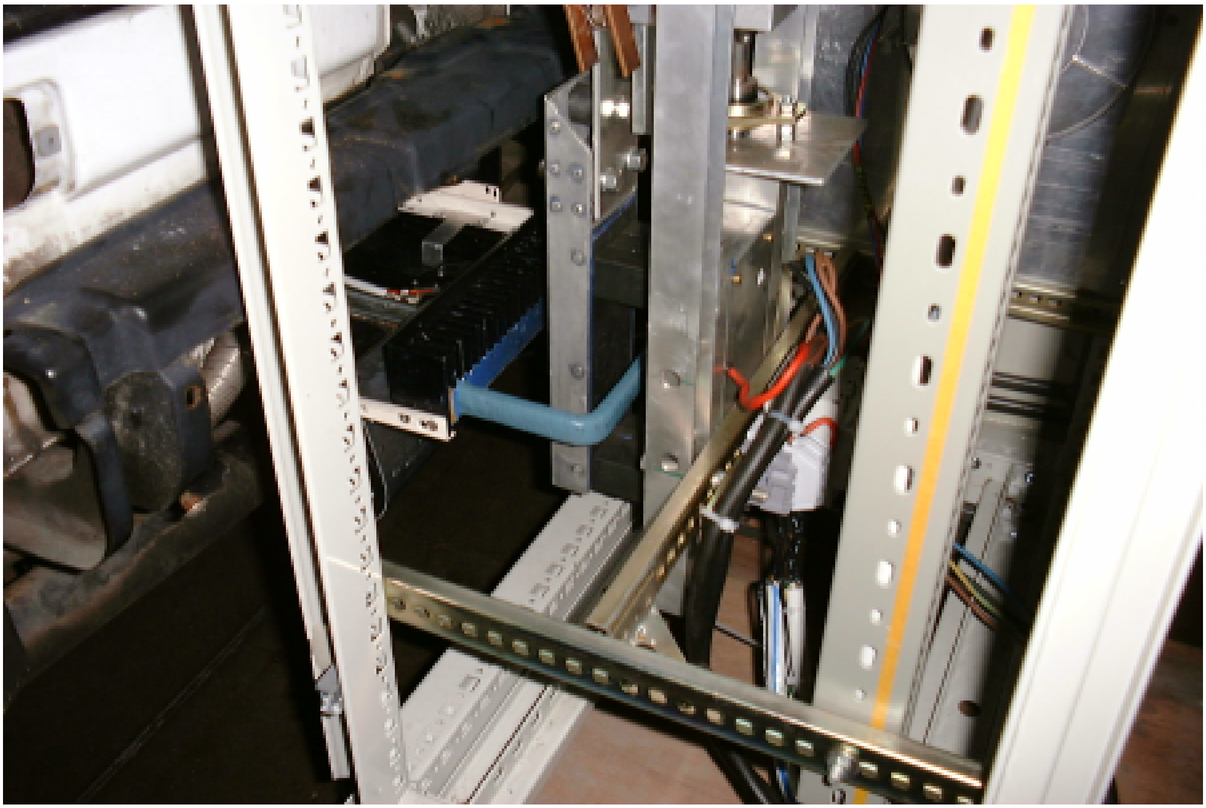


Fig. 18 : Prototype of Chained-Ring structure
Ground casing (underpart)
Moving core in “closed” position

A tested structure is shown in Fig. 19. The results are given in table-6.

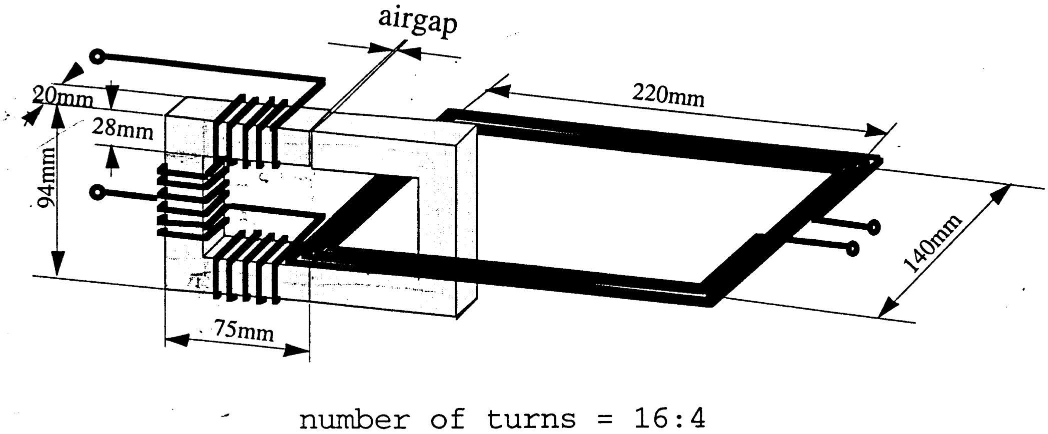


Fig. 19 : Model of the chained-ring type for test

table-6 parameters of the chained-ring type inductive coupler

Air-gap	R1	Ldl	M	R2	Ld2	k	d
0 mm	9mΩ	27μH	1483μH	203mΩ	108μH	0.956	0.972
0.25mm	9mΩ	18μH	428μH	203mΩ	124μH	0.863	0.898
0. 50mm	9mΩ	16μH	297μH	203mΩ	128μH	0.814	0.858

†The resistance are calculated dc value with 590/00.09 litz wire.

†† All the secondary parameters have been reduced to the primary.

7.6 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.
This can be realised by an IR or RF communication link.
Fig. 20 shows the principle structure of the control loop.

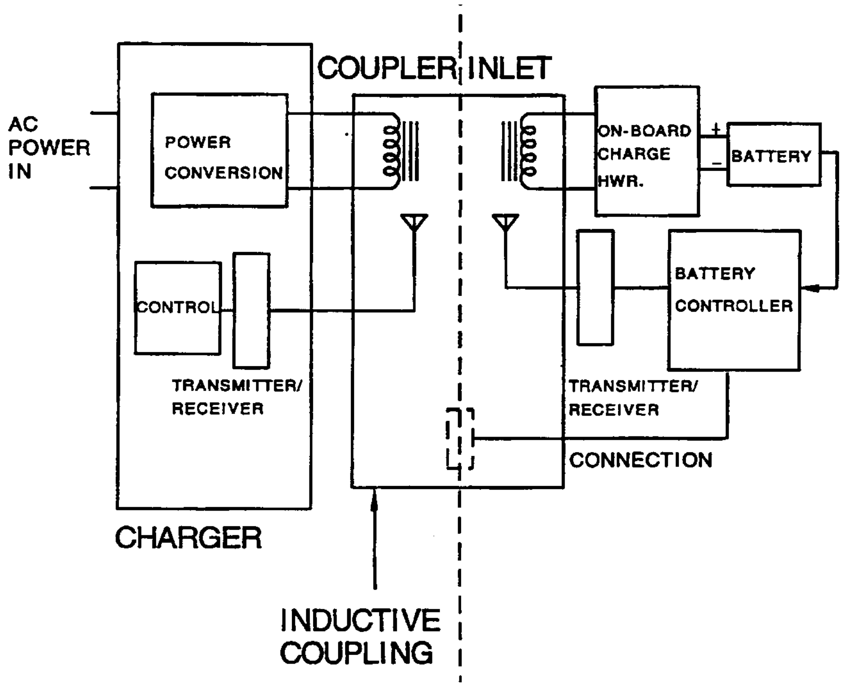


Fig. 20 : General aspect of inductive charging system

-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.

7.7 Efficiency

Measurement System Composition

The measurement system is composed of the VUB - EVIAC charging station, the Electrical Vehicle charging circuit, a self-made RMS and average power measurement card, DAS card (AX5621H DAS Card) and a PC. The diagram is shown in Fig. 21.

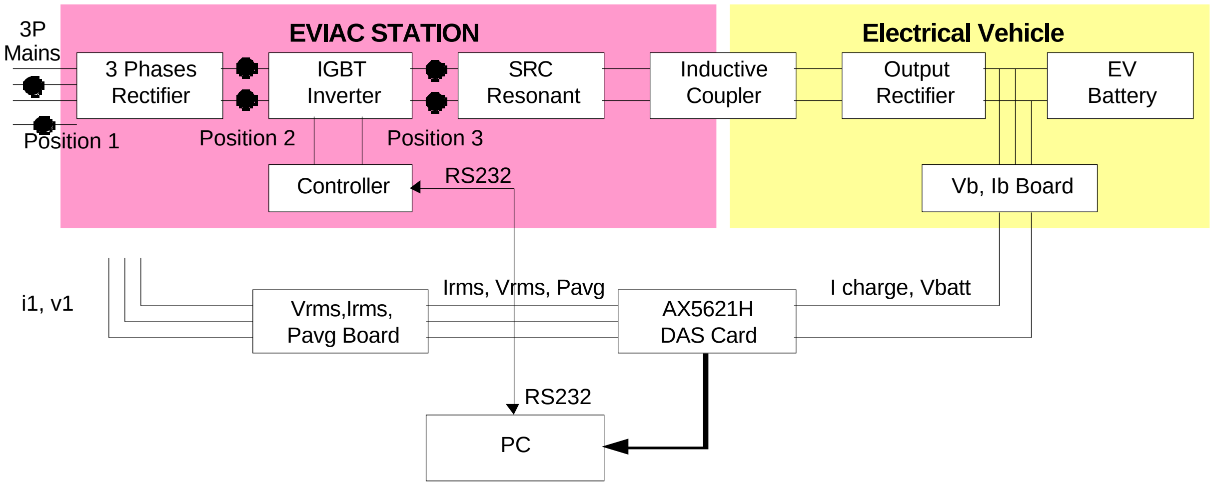


Fig. 21 : Structure of efficiency measurements

The PC has two roles here:

- To control the operation of the VUB - EVIAC
- To take and record the measurement

Three kinds of control modes have been implemented in this system:

- Constant current control mode (from 0 to 50A)
- Constant voltage control mode
- Constant duty cycle control mode (from 0 to 65 A)

By connecting the transducers of i1 and v1 at different position on the charging station side, the efficiency and PF of the different parts can be measured:

- Position 1 refers to the measurement of the whole system efficiency
- Position 2 refers to the measurement of the DC-DC converter efficiency

Position3 refers to the measurement of the SRC resonant tank and output rectifier efficiency

The measured efficiency curve looks as shown in Fig. 22.

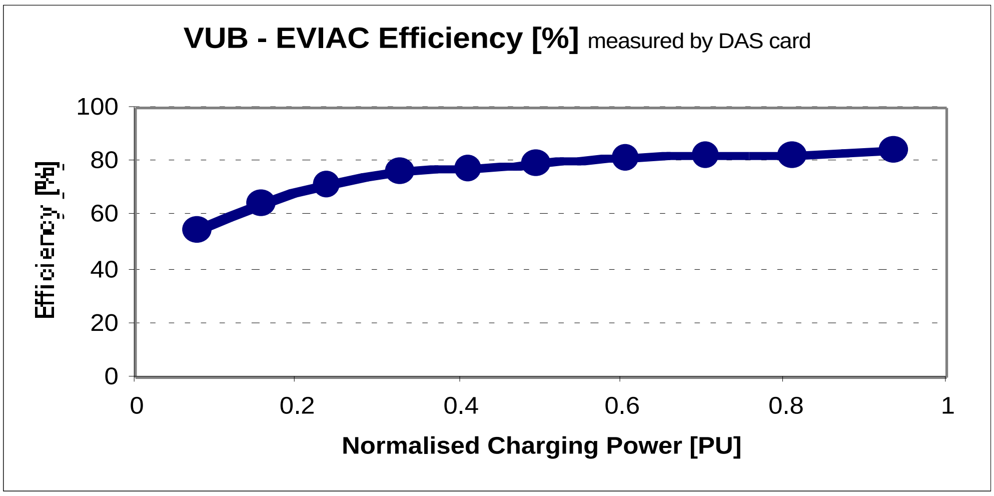


Fig. 22 : Efficiency curve

The average power at rated charging power level has the distribution shown in Fig. 23.

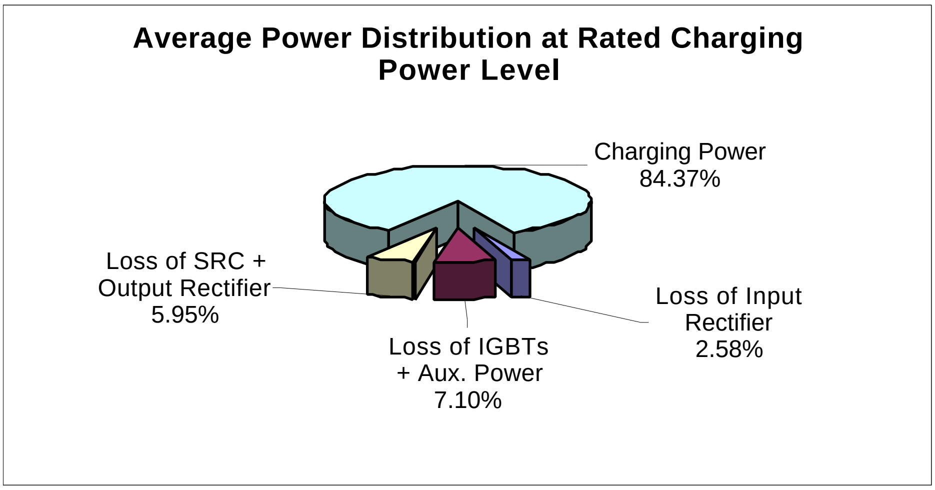


Fig. 23 : Power distribution in the charger

This allows eventually the development of design efforts to reduce some losses. Considering the characteristics of battery charging it is important to have a high efficiency at full load but also a rather high efficiency at low load. Indeed low load corresponds with the need phase of charging which occurrence is more or less frequent depending of the energy management on board the vehicle and the way the vehicle is daily used and reconnected for charging.

7.8 Comparison between the different types

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

7.8.1. 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-7.

table-7 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

7.8.2 Comparison of the parameters.

The insertion type coupler has the most compact structure. Its core section area and the volt per turn value can be large. The leakage inductance and the damping resistance of both primary and secondary inductors are small. The magnetising inductance is high.

The disc-shaped proximity type coupler, on the contrary, spreads its windings over a large surface. The volt per turn value cannot be high. The leakage inductance and the damping resistance of both primary and secondary inductors are relatively large. The magnetising inductance is small because of the big air-gap.

The chained-ring type coupler has the most loosely mechanical structure. Its core section area may not be very large because of the shape. The volt per turn value may be as high as for the insertion type. Both the leakage inductance and the damping resistance are small at the primary side but large at the secondary side. The magnetising inductance is large, due to the possible limitation of the air-gap of the magnetic core introduced by its moving part.

The parameters of different type of couplers are fuzzily classified in table-8 for comparison. It should be noted that the comparison should be based on some conditions like comparable power rate and comparable current density.

table-8 summary of the parameters of the inductive couplers

type	R1	Ldl	m	R2	Ld2	k	d
Insertion	small	small	large	small	small	good	=1
Proximity	large	large	small	large	large	bad	=1
Chained-ring	small	small	large	large	large	medium	<1

† The parameter d is characterizing the symmetry.

7.8.3 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 (table-3) 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-9 for a quick comparison.

table-9 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

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