Review of Contactless Energy Transfer Concept Applied to Inductive Power Transfer Systems in Electric Vehicles

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Review

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Abstract: Nowadays the groundbreaking tools of contactless energy transfer reveals new opportunities to supply portable devices with electrical energy by eliminating cables and connectors. One of the important applications of such technology is the energy providing to electric and hybrid vehicles, (EV) and (HEV). These contribute to the use of cleaner energy to protect our environment. In the present paper, after exposing the contactless energy transfer (CET) available systems, we examine the appropriateness of these systems for EV. After such exploration, it is shown that the most suitable solution is the inductive power transfer (IPT) issue. We analyze such procedure in general and indicate its main usages. Next, we consider the practice of IPT in EV and the different option in the energy managing in EV and HEV concerning battery charging. Following, we review the modes of using the IPT in immobile case and in on-road running. Following, the modeling issues for the IPT system escorting the vehicle structure are then exposed. Lastly, the electromagnetic compatibility (EMC) and human exposure analyses are assessed involving typical appliance.

Keywords: contactless energy transfer; inductive power transfer; electric vehicle; static and dynamic charging; modeling; EMC

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1. Introduction

Most recently, contactless energy transfer (CET) practices have developed more advanced and explored directions. This pioneering technology reflects new opportunities to supply portable devices with electrical energy by eliminating cables, connectors, etc. Such devices traditionally employ a normal cable connection for charging which may contain difficult items for the user and CET becomes an interesting substitute. This rises consistency of such schemes in crucial usages such as aerospace, biomedicine, multi-sensor applications, and robotics.

Various techniques are used for constructing CET devices. The modus operandi of these is classified conferring to the means used for energy transfer between the transmitter and the receiver [1–4]. These CET devices could be acoustics-based [5–10], light-based [11–14], capacitive based [15–18], and the greatest set, inductively coupled ones. This last is particularly used in EV as will be discussed in the next section.

The two basic theories that accomplish CET using inductive power transfer (IPT) are the Ampere's law of 1820 and the law of magnetic induction discovered by Faraday in 1831. Whereas Ampere revealed that a current could engender a magnetic field, Faraday shown the dualism among the magnetic and the electric field explaining that a time-changing magnetic field interacting with an electrical circuit induces into it an electromotive force. These two principles permitted plentiful applications directing the expansion of the new energy conversion devices. The most basic real improvement in the way of IPT appeared with Tesla's explorations. Nikola Tesla first initiated wireless power transfer in the 1890s [19], however it is only newly that this expertise has been extensively utilized for common applications. This is especially due to the amplification of high frequency resonant wireless energy tools for the charging of various daily devices. The principle of electromagnetic induction investigated experimentally in 1831 by Michael Faraday [20], finds its main use is the classic transformer that having a closed magnetic circuit to concentrate the engendered flux.

Their main applications include EV and battery chargers, robots, winches, mobile devices, sensors and actuators. Aside from EV, the IPT technology is employed in many other devices. We can mention low-power chargers (e.g., for mobile phones), medical healthcare treatments (e.g., energy transfer to embedded implants) [21–23]. Also we find IPT technology in rotating elements (e.g., for radars and aeronautics) [24], links in difficult environments (e.g., drilling devices, underwater apparatus, explosive airs . . .) [25–27], auxiliary power supply of magnetic levitation trains [28,29]. In addition to these applications, many works about the IPT system and its applications could be found in the literature, see e.g., [30–36]. Moreover, concerning high frequency resonant wireless energy tools for CET and IPT, many works regarding resonant converters have been published, see e.g., [37–43].

In the present work, we examine first the appropriateness of the different CET available systems for EV. Then we analyze Inductive power transfer IPT in general and point out its main applications. Afterward, we discuss the use of IPT in EV and the different option in the energy managing in EV and hybrid EV concerning battery charging. Next, we review the modes of using the IPT in stationary parking and in road driving. The modeling issues for the IPT system associated with the vehicle structure are then exposed. Finally, the electromagnetic compatibility (EMC) and human exposure analyses are illustrated.

This article does not claim to present an exhaustive review of all areas concerned with wireless energy transfer. There are many reviews and technical papers published in these different fields where researchers and engineers involved in the subject can find almost all the technical details. This article aims to provide a general literature-based overview of the different options involving wireless energy transfer and to discuss tools for assessing system performance and compatibility. The challenges resulting from the review are discussed and the various investigative challenges arising from the analysis are presented.

2. CET Systems and EV

As mentioned in the introduction the actual CET devices could be acoustics-based, light-based, capacitive based and, inductively coupled ones. We will survey these four issues and examine their adequacy regarding battery charging in EV.

2.1. Main Features of CET Devices

The acoustic CET Systems [5–8] use two piezoelectric transmitting and receiving transducers converting electric-acoustic (pressure)-electric energy. These systems have different advantages. They can be used where electromagnetic (EM) fields are not allowed and they have smaller dimensions when high directionality is required. Normally, their efficiency is less than that of the inductive ones; but, when the distance transmitter to receiver is much larger than their radii (ranges), their efficiency can be higher [5,9]. Representative applications of acoustic CET systems involve biomedical (with a power up to 100 mW and efficiency up to about 40%), across-wall sensors for metal inserts (nuclear systems, vacuum chambers, gas cylinders . . .) transferring 1 kW at 84% efficiency [10].

Light CET Systems use Laser diodes to produce an optical power ray and photovoltaic diodes to transform it back into electrical energy. Their efficiency and practical applications turn out to be limited when operated over long spaces because of diffractive losses. The power level is very small (1–10 W), and optical to electrical conversion efficiency is 20–30% [11–14]. Applications principally embrace spacecraft platforms and terrestrial technologies [11,12].

Capacitive CET Systems use two primary metal plates and two isolated secondary plates connected to electronic converters to transfer electric energy. The surfaces of the coupling metal plates are layered with dielectric to offer isolation and to rise the coupling capacitance [15–18]. Opposing to inductively coupled CET, the capacitive CET uses an electric field and metal barriers. Owing to the constricted character of the electric field between metal plates, it also has the capacity to bring down EM interference (EMI). The power level and efficiency are between 5–50 W and 50–80%, respectively. Their usual uses include power sources to light-emitting diode (LED) lamps, mobile phones, sensors for respiratory machines [15,16].

Inductive CET Systems consist mainly of a big air gap transformer and resonant converter. The transformer possesses isolated sides (primary transmitter and secondary receiver) that can be mobile. Between the source and the primary, a dc/ac high frequency resonant converter is inserted. Linking the secondary to the load, an ac/ac resonant converter with load-adapted frequency is employed.

For more details, concerning figures illustrate different CETs; one can consult e.g., [1], for acoustics, light, capacitive and inductive, see respectively, (Figures 2–5, pp. 48–50 in [1]). Also in the same reference, a table to compare and contrast different CETs is given, (Table 1, p. 49 in [1]).

2.2. Appropriateness for EV

The CET using acoustic waves presents advantage of being operational in situations where electromagnetic emissions are proscribed. In addition, transmission can happen across metal walls, which is appropriate for sensing in e.g., nuclear structures. Conversely, the powers implicated do not match to EV applications. Moreover their efficiency diminutions severely with the gap between the transmitter and the receiver, which handicap the use in EV.

The optical power laser ray might be an answer, but that uses concentrated huge energy on a slight exceptionally directional beam. This presents evident safety complications in the perspective of EV case whilst driving. Furthermore, the present powers are very low.

CET by capacitive coupling [44–48] can be envisaged in case of EV. This solution has the advantage of being less sensitive to the shift in the coupler than transmission by induction, but the functioning seems complicated and particularly involves high voltages at the terminals of the coupling capacitors. In addition, the distance between reinforcements leads to low capacities and implies operating at very high frequencies, greater than one mega Hertz [49].

Inductive CET seems the most appropriate for EV applications. It allows energy to be exchanged between two systems without any electrical connection between them. It, as mentioned before, consists mainly of a big air gap transformer and resonant converter. The main applications of inductive power transfer IPT include in addition to EV and battery chargers, robots, winches, mobile devices, sensors and actuators. In the case of transport sector, the technologies based on inductive coupling are used for power transfer to electric or hybrid vehicles, whether they are buses, trucks, or automobiles. This include static charging when stationary and dynamic charging while driving the vehicle.

3. Inductive Power Transfer IPT in EV and Hybrid EV

In the case of EV power transmission, the magnetic circuit can be almost abolished and the gap between the two coils is usually greater. This will lead to an important flux leakage. We will see later how to deal with such a problem.

The IPT offers in the occurrence of EV a simplicity of use, a speed and a suitable resistance to the injury. The purpose is to transfer energy from the ground to the vehicle-embedded battery by means of an inductive loop system as shown in Figure 1. This device necessitates getting a worthy performance and right positioning tolerance to permit a decent transmitter—receiver coupling. The coupling between the transmitter, positioned on the ground, and the receiver, located under the bottom of the vehicle, is operated across a considerable gap. This large distance infers an elevated quantity of parasitic field adjacent to the coils, which can present a difficulty of exposure to magnetic fields for vehicle travelers or persons about to approach the vehicle thru charging tasks. It is hence needed to estimate the intensity of exposure to comply with international security directives ICNIRP [50].

IPT systems could be operated in static, car parks mode [51–57] or when running [49, 58–63]. The dynamic mode, yet more complex in its functioning control and the necessity for particular infrastructures, presents the opportunity of beating the obstacles correspond to the weighty battery storage aboard, the lengthy charging period and the restricted autonomy in the static mode. The parasitic field intensity neighboring the coils owing to a great air gap can be dissimilar among static and running modes. This is because of the type and function of the coils in both circumstances. Furthermore, the restrictions of field exposures change concerning the two modes.

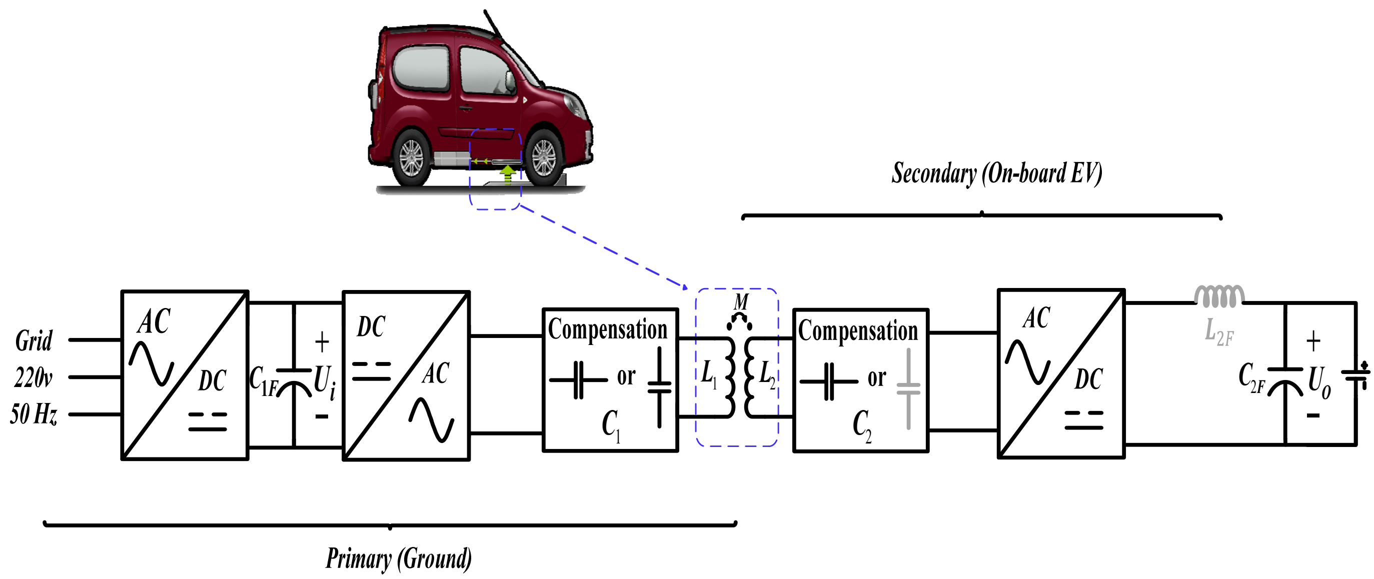

Figure 1. Schematic diagram of IPT (inductive power transfer) charging system for EV (electric vehicle), [52].

Concerning energy managing in EV and hybrid EV, we can summarize the different battery charging possible situations. The basic options are the full electric vehicle EV that is externally rechargeable and the hybrid thermal electric vehicle HEV that is internally rechargeable by the thermal mode. The HEV could be also externally rechargeable in addition to the internal mode (RHEV). Both the EV and RHEV could be designed to be recharged in one of the two modes statically or while travelling. Moreover, they could even be constructed to be recharged in either of the two modes.

The next sections are relative to battery charging in both EV and RHEV.

4. Static Battery Charging

A schematic diagram of an IPT charging system for an EV is symbolized in Figure 1. It is constituted of a source, a load and in the middle an inductive coupler transformer (ICT) with shielded coils. Planar parallel axes screened coils could yield regarding the ICT assembly, a dexterous magnetic flux transfers. In such a condition, the energy transfer operates on the entire receiver face and shielding is exploited to enhance the mutual inductance (M) by growing the magnetic flux linking the two coils. The shielding is achieved by a magnetic practically none conducting material and ferrite is habitually used.

The full scheme is constituted of two main elements: the ICT that permits the wireless transfer thru the magnetic induction and that guarantees a galvanic insulation concerning the source and the load. The second element involves the capacitive compensations and the power electronics linked to ICT, which accomplishes the procedure to operate at resonance. The whole scheme performs IPT system. Sandwiched between the grid and the ICT, two conversion stages: grid low frequency ac/dc, and dc/ac high frequency. These conversions permit adjusting the power amount by monitoring the input voltage and the frequency.

Stuck between the ICT and the battery, a final conversion from high frequency ac/dc allows granting energy to the battery. As the airgap of the ICT is great, the coupling is weak. Consequently, to achieve the demanded transmitted power, important reactive power need to be directed, so the usage of resonant elements [37–43] in both sides of the ICT is essential as compensation to ensure good efficiency. Furthermore, the output parameters at the load part should be monitored in order to supervise the charging profile of the battery and to assure its protection.

An assembly of the ICT coupler is presented in Figure 2. It contains a transmitter coil, a receiver coil and two ferrites plates that totally cover up the coils. A steel plate acting for the EV chassis is inserted in the design. The ICT two coils with their ferrites in the situation of Figure 2 are identical with an air gap (d), and axes shift (sh) which corresponds to the EV position on the ground. These two parameters are directing the design and the performance of couplers [51–57].

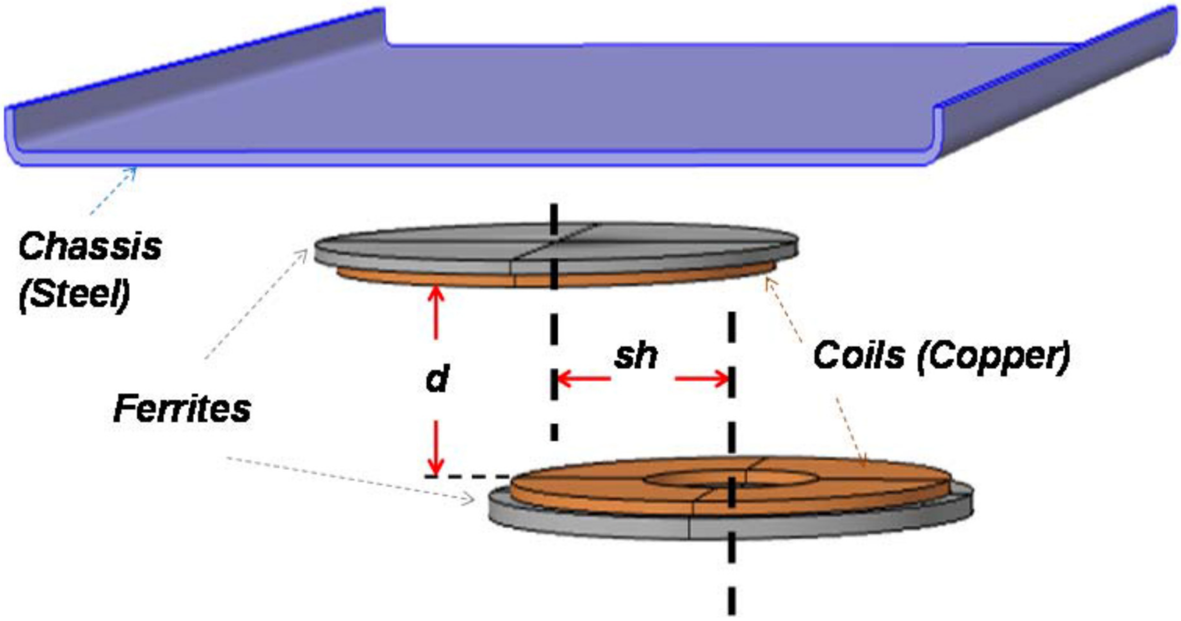

Figure 2. 3D structure of an ICT with shielding and a simple EV chassis, [52].

Interoperability Analysis

In public requests circumstances, the two coils and usually pads (coils/ferrites) shapes may be dissimilar subject to constructors of EVs and IPTs. One of the inconveniencies is the big number of structures industrialized not including any compatibility in-betweens. Consequently, we need to accomplish an interoperability analysis [52,64–68].

In exercise, we require an interoperability analysis regarding the figures and surfaces of the pads of groundside regarding those of EVs. Such analysis involves the position of EV pad of the vehicle (middle or backend), the tolerance to locating of vehicle, the human exposure recommendations, the IPT efficiency, the dimensions of power components of the IPT . . . Actually the problem of interoperability is one of the most vital and imperative for vehicle constructors as well as energy providers. This is unmodified in both charging modes, the static and dynamic ones. The corresponding studies are sporadic and just initiated recently. A complete investigation of this enquiry is accessible in [32,46].

5. IPT in EV on Road

As mentioned before static IPT technology designated as static when the vehicle is immobile during charging, that likely substitute the wired systems. In the case of dynamic IPT, the receiver installed on the lowermost of the vehicle will progress over successive transmitters embedded on the ground infrastructure.

The setting in place of dynamic IPT schemes in the road infrastructure will eliminate the necessity for charging halts and could result in a noteworthy reduction in the size of the on-board battery [38–43]. The fruitful illustration of the practicality of this technology may point out a tangible media to increase the reception of electric mobility and to deal with the furthermost critical features of the use of EV.

A central technical difficulty in the dynamic IPT is the detection of the vehicle when it accosts a transmitter and the controlling of the passage between successive transmitters. Such detection and control need precise and robust technics see e.g., [61,62,69]. Moreover, as in static IPT, there is the facet of security touching exposure to fields generated in the dynamic IPT.

Finally, there is enormous amount of challenges signified by all the features related to the founding of the road infrastructure. In specific, the enclosure of the emitting segment in the pavement, the selection of stuff for the coating, the administration of the rainwater, the requirement to communicate with the involving management infrastructure. Different recent labors are related to these facets; see e.g., [59].

6. Modeling in IPT Systems

Expressions characterizing the behavior and permitting the design and optimization of IPT systems as well as equivalent circuits involving the ICT features and the resonance topology for a specific compensation could be found in many references for both of IPT systems, the static one, e.g., [51–57] and the dynamic one, e.g., [49,58–63].

This section regards the determination of the parameters involved in these expressions and equivalent circuits based on realistic 3D electromagnetic computations of the ICT accounting for representative electric circuits.

Mathematical modeling in electromagnetic systems (EMSs) often uses 2D or 3D numerical computations, see e.g., [70–79]. Such models are understood to be validated by observation [80]. Mathematical modeling in IPT systems is used in view of different objectives.

The first is related to the determination of the IPT electric circuit parameters accounting for the electromagnetic behavior of the ICT. The second concerns the behavior of the different variables in the IPT electric circuit and the system efficiency. The third aspect is relative to the electromagnetic compatibility (EMC) analysis [81–85] that is relative to the emission perturbations introduced by involved fields for the functioning of the EV, for the EV occupants and the surrounding. The last aspect of modeling is relative to the design and optimization of the IPT features to comply with the constraints regarding the EMC.

6.1. Determination of the IPT Electric Circuit Parameters

Concerning the IPT circuit parameters, in general we can practice 3D electromagnetic field computations for the ICT, with for example the finite elements method (FEM) simulations, counting for the whole structure of the IPT (see Figure 2), to obtain its mutual coupling and inductances (see Figure 1). This considers the source voltage and frequency as well as the geometric positioning of the coils (parameters d and sh, Figure 2). Moreover, the influence of shielding by means of coil-closed ferrites to decrease the leakage fields and to limit the infiltration of the field within the vehicle is counted in such simulations. Furthermore, the EV chassis is also modeled in the configuration of the IPT system [52]. Actually, the existence of the EV chassis alters the field values, and hence the matching inductances of the power system and the electromagnetic compatibility (EMC) emission level.

This can be achieved by solving the system of Maxwell equations. This equation system can be formulated mathematically under different forms function of the considered problem. One of the most common is the basic full-wave electromagnetic formulation given by:

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{1}$$

$$\mathbf{J} = \sigma\, \mathbf{E} + j\, \omega\, \mathbf{D} + \mathbf{J_e} \tag{2}$$

$$\mathbf{E} = -\nabla V - j\,\omega\,\mathbf{A} \tag{3}$$

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{4}$$

where (**H**) and (**E**) are the magnetic and electric fields, (**B**) and (**D**) are the magnetic and electric inductions, (**A**)and (V) are the magnetic vector and electric scalar potentials. (**J**) and ($\mathbf{J_e}$) are the total and source current densities, (σ) is the electric conductivity and (ω) is the frequency pulsation. The symbol (∇) is a vector of partial derivative operators, and its three possible implications are gradient (product with a scalar field), divergence and curl (dot and cross products respectively with a vector field).

The magnetic and electric behavior laws respectively between **B/H** and **D/E** are characterized by the permeability (μ) and the permittivity (ε).

The solution of the Equations (1)–(4) permits to determine in a system with a given 3D geometry the concerns of electromagnetic fields for a frequency pulsation accounting for the magnetic materials behaviors through the permeability, for eddy currents in electric conductors through the electric conductivity and for displacement currents in dielectrics through the permittivity.

6.2. Behavior of the IPT Electric Circuit

Often, EMSs involve other fields than EM, for example mechanic, thermic, material ... In some cases, the influence of these other fields could be negligible and it will be then possible to solve the problem correctly with only the Maxwell's equations, see e.g., [77,79,82,85]. Nevertheless, in such case, there is yet a conflict with real situations. In realistic applications the electric current is delivered by a non-perfect current source as supposed in Equations (1)–(4) that consider the current delivered by a current source. The committed assumption is that we consider in Equations (1)–(4) the value of $\mathbf{J_e}$ known and could be imposed. In general, the current is delivered by a voltage source through an external electric circuit. The general next relation, between the voltage (v) and the current (i), in the external circuit (coil) governs this current:

$$v = \frac{1}{C}\int i\,dt + r\cdot i + L\,\frac{di}{dt} + \frac{d\Psi}{dt} + 8 \tag{5}$$

In this expression (r) is the total resistance of the circuit, (L) a linear inductance, (C) a capacitor, (8) a non-linear voltage drop (typically a semiconductor component, e.g., a diode) in the electrical circuit and (Ψ) the flux linkage in the coil.

The flux linkage in Equation (5) is determined from Equations (1)–(4) and the obtained current from Equation (5) should be the input in Equations (1)–(4). Strictly theoretically Equations (1)–(4) and Equation (5) should be solved simultaneously in a coupled model. This is because the two equation systems involve non-linearity (magnetic—μ and electric— 8) and the concerned time constants (electric and magnetic) are of the same order [80]. However, a sequential approximate solution could be performed in the present case [52,53].

After determining the mutual coupling and inductances of the IPT circuit taking into account the ICT structure from the field values, the electrical circuit model Equation (5) of the whole system could be determined, including the resonance topology (Figure 1). The behavior of the different variables and the efficiency could be simulated from such a model [52,53,86–89].

7. EMC Analysis and Human Exposure in EV

As mentioned previously, the coupling of the transmitter, located on the ground, and the receiver, placed under the bottom of the vehicle, is done through a large gap. Such a large gap in the mid of the two ICT coils in static or dynamic cases infers a high level of stray field close to the coils. This condition poses a challenging exposure to magnetic fields for vehicle travelers or people (or things) expected to be close to the vehicle in the course of charging maneuvers. Therefore, to conform to the health safety, it is required to assess the degree of exposure with regard to the international safety guidelines labelled by the

International Commission for the Protection against Non-Ionizing Radiation (ICNIRP) [50]; the highest limits are 27 µT for the magnetic induction B and 4.05 V/m for electric field E.

Two characteristics relate to the interactions of the IPT structure and the human body. The first is to evaluate the electromagnetic fields (**B, E** and **J**) induced in the human body at the IPT frequency. The second is to inspect the effect of the IPT system input current on the radiation heights and to make accessible the effective data to determine the degree of the design freedom of the IPT systems. It should be noted that owing to electromagnetic compatibility and energy efficiency, the IPT system for EV commonly functions in a comparatively small frequency scale (from a few kilohertz to about 100 kHz).

For the prediction of radiated fields, we need adequate modeling tools [81–85]. The assessment of exposure of alive matters to magnetic fields requests in general suitable modeling approaches founded on 3D computations used for solving the electromagnetic problem Equations (1)–(4) containing the IPT system, the vehicle and the humans (in the vehicle or situated nearby). In such computations, the considered model of human body is very significant. The most decisive aspects ruling the acceptance of such a model are the consistency with physical biological qualities of faithful circumstance and the agreement to the used computational approach.

7.1. Human Body Model

Generally, the computations of electromagnetic fields in human body necessitate a sufficient data of the dielectric properties of human tissues for an identified frequency. The consequent models are of two refinements, homogeneous and inhomogeneous. For the first ones, the dielectric belongings are generally endorsed to a 2/3 equivalent muscle model [90]. For inhomogeneous models, ghost models of layered stuff are built on magnetic resonance imaging (MRI), computed tomography and arithmetic imaging techniques, offering exactness of tissue profile to the nearest millimeter [91,92]. The dielectric properties of biological substances are illustrated in [93] where a complete image of the accessible measurement data for dielectric permittivity and electrical conductivity for any identified frequency is indicated.

7.2. Fields in the Body Tissues

Regarding the conformity with international standards, we need to estimate the fields adjacent to the IPT system that can create elevated fields in the body tissues of proximate humans. We need also to typify the conditions under which the IPT system can confirm accord with international safety rules ICNIRP [50], and IEEE Standard [94].

The estimation of exposure of human tissues to magnetic fields needs appropriate and ample modeling practices based on 3D computations for solving the electromagnetic problem linking the IPT system, the vehicle and the human body, see [95–98].

A typical evaluation of such a problem needs the determination of the electromagnetic fields induced by a representative IPT system in the human body. This must involve a human anatomical model with high resolution, but compatible with the numerical methodology, built from human MRI models, see e.g., ([95], Figure 2). A 3D numerical approach based on the solution of (1–4) providing an estimate of human exposure can be applied for position configurations of humans involving normal and unfavorable situations (Figures 3–7 in [95]).

A crucial point in such problems is that the height of exposure is amply reliant on several parameters: shape and size of coils, geometrical features of the system (structural parts of the vehicle and shielding plates), materials properties (ferrites and chassis of vehicle), misalignment of transmitter and receiver whereas charging, and position of the human body. Furthermore, each physical or geometrical parameter may be concerned by some uncertainty. Consequently, during the design of the IPT system, the consideration of level of exposure cannot only rely on deterministic full 3D solvers. In situation, one need to study the sensitivity of the exposure degree taking into account the uncertainty of the parameters describing the electromagnetic problem. Subsequently, the introduction of stochastic tools permits dealing with the changeability of all the parameters relating the electromagnetic problem [99].

8. Discussion and Conclusions

Following the precedent analysis, we will first call attention to the evolution of energy managing in mobility concerns in generally. We are going to point out the elements influencing such evolution historically and in foreseen future.

First, constraints in terms of CO2 emissions pushed automotive industry manufacturers to develop a "cleaner" concept such as electric vehicles (EV) and hybrid electric vehicles (HEV) to replace full thermic vehicles. Note that the battery storage is much more important in the case of EV compared to HEV.

EV, at the moment, presents a limited autonomy due to the battery character and HEV becomes a significant concurrent. Nevertheless, HEV still has an important part of thermic dependence that related again to the limited autonomy of the electric part. So, the solution of rechargeable hybrid electric vehicle (RHEV) becomes interesting. So, one can control the partition of the thermic and electric parts. Note that RHEV is equipped normally with more battery storage than the HEV and less than EV.

EV and RHEV presently uses a cable link for static charging which may include annoying and/or inconvenient items for the user. In this context, the contactless inductive power transfer (IPT) static charger is an interesting substitute. Thus, such static IPT technology designated as static when the vehicle (EV or RHEV) is immobile during charging, that likely substitute the wired systems.

However, we can go further in direction of more edgy option with the possibility of using the inductive transfer when travelling, that using the dynamic IPT. Furthermore, we can use IPT operating in both modes static or dynamic.

We can imagine a hybrid vehicle rechargeable statically or while traveling. This will offer all the possibilities of energy supply. The vehicle could be operated in thermal or electric mode and the battery could be charged statically or while driving. In such a case, the partition between the different energy sources could be managed to be, for each, from little to full depending on the circumstances. In this case, we have to compare the gain in comfort and time compared to the complexity of the devices required and the cost of the infrastructure.

The investigations followed in this paper concerned several questions regarding contactless energy transfer applied to mobility. This involved the system choice, the transfer options, the systems interoperability, the modeling strategies and the electromagnetic compatibility with human exposure analyses.

The inductive power transfer IPT appears to be the most appropriate for electric vehicles. The battery-charging mode in stationary parking that avoiding cable connection requires the use a relatively simple IPT with simple position adjusting for efficient transfer. Nevertheless, an interoperability analysis is necessary to permit standardization for compatibility of different IPT systems.

The dynamic road-driving mode is more practical and less time consuming. However, this mode uses a more complicated IPT with smart sensors and control strategies as well as communication devices. Moreover, the needed infrastructure for this mode is high-priced and requires regular care. Nevertheless, these problematical aspects possibly will look like negligible in the near future regarding the increasing number of electric vehicles and the evolution in smart technologies as well as autonomous vehicle (AV) skills.

From this review, we noticed that research in the field of wireless energy transfer is very active and considerable in the literature. The challenges in this topic resulting from this review are diverse, technical, economic, societal, security, environmental ... They involve different expertise, electrical, mechanical, electrochemical, electromagnetic, material, infrastructure, industrial compatibility, health, societal tolerability ...

The different EV options using IPT technology are the full EV and the RHEV. Both can use IPT in static or mobile mode. The challenges in each of these situations may be different.

In the case of full EV, challenges mainly concern autonomy, battery technology, vehicle weight, industrial interoperability and infrastructure in case of travel mode for long distance transport.

* Battery technology is linked to innovations in electrochemical research to achieve high capacity with low mass and volume.
* The reduction in the weight of the vehicle apart from the problem of the battery, concerns the new materials of the structure. This implies safety expertise in the field of mechanical and electromagnetic compatibility (EMC).
* Apart from transport close to home where the EV usually uses an identified IPT, the problem of interoperability of IPT installations appears to be a critical difficulty.
* In the case of a mode of travel for long-distance, the question of infrastructure poses specific technical and economic problems. The first concerns the adapted technologies taking into account uncontrolled weather conditions, the optimization of the primary ground side of the IPT, the intelligent communication between the EV and the infrastructure system, the organization of flows and the management of interoperability. The economic problem mainly concerns the size of the demand due to the obvious viability of the installation.

In the case of the RHEV, the problems of autonomy, battery and weight are relatively reduced. The issues of interoperability and infrastructure for the mode of travel can be circumvented. However, the issue in this case concerns the dual use of dexterous and clean engines with high efficiency with minimal pollution.

Different investigative challenges emerge from the last analysis. These mainly concern battery technology, new compatible structural materials, interoperability of IPT installations, infrastructure technology and optimization of IPT for the mode of travel.

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