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Inductive power transfer for automotive applications: state-of-the-art and future trends

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Abstract—The paper discusses the development status of the inductive power transmission for automotive applications. This technology is, in fact, gaining the interest of electric vehicle manufacturers as an effective strategy to improve the market penetration of electric mobility. Starting from the origin of this technology, the paper presents an overview of the current state-of-the-art as well as the current research and industrial projects. Particular attention is devoted to the description of a prototypal system for the dynamic inductive power transmission whose goal is to extend the battery range by a fast partial recharging during the movement of the vehicle.

Index Terms—Wireless power transmission, inductive power transmission, electric vehicles, resonant systems.

I. INTRODUCTION

Electricity is a very common vector to convey energy, and its wireless transmission has been of interest of researchers for centuries. Remarkable examples are Faraday's experiments on electromagnetic induction and energy transmission through fluids in 1832 [1], the applications of the radio frequencies communications investigated by Hertz in 1895 [2], and the Tesla's experiments on the wireless electric energy transmission at long distances [3] in 1904. In the last decades, the scientific community has defined as *wireless power transmission* (WPT) the different ways to transfer energy at distance without wires. Today this definition covers several technologies in a wide range of applications, power and distances. Fig. 1 schematically shows the most common technologies for WPT involving electromagnetic fields [4]. WPT technologies seem to represent an effective way to reduce the problems of costs and management of the batteries installed on electrical vehicles (EVs) eliminating the major barrier to the electro-mobility diffusion. In this paper, the authors provide a review of a particular technology in the domain of WPT called *resonant inductive power transmission* (IPT) for the charge of electric vehicles.

II. THE RESONANT INDUCTIVE POWER TRANSMISSION

The two fundamental principles that govern the IPT are the Ampère's law of 1820 and the principle of magnetic induction discovered by Faraday in 1831. While Ampère proved that a current can produce a magnetic field, Faraday showed that a time-varying magnetic field interacting with an
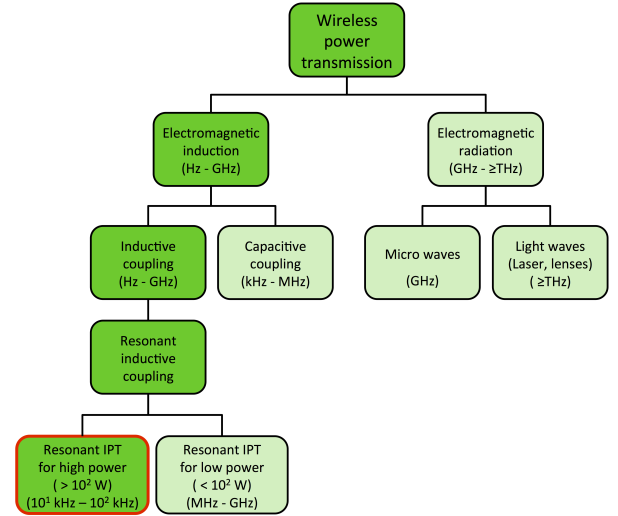

Fig. 1: Different methods for the WPT using electromagnetic fields and waves. The red frame indicates the technology investigated in this work.

electrical circuit can induce into it an electromotive force. These two laws allowed countless applications, and led the development of the modern electric machines. Tesla coined the definition wireless power transmission [5], and presented a contactless system at the World Exposition of Chicago in 1893. Seven years later Tesla obtained the patent for an apparatus for the wireless transmission of electrical energy over long distances using inductors, in which he identified two important parameters of the inductive transmission [6]:

1) the increase of frequency to improve the power transfer capability.
2) the use of capacitors (i.e. a Leyden jar in the Tesla's prototype) connected to the coils to create a resonant system and improve the effectiveness of the transmission.

A functional block diagram of an IPT system for EVs is depicted in Fig. 2. It basically consists of the inductive coupling between a coil above or below ground, defined as the transmitter, and a movable coil placed under the vehicle, defined as the receiver. The transmitter is powered through a power electronics converter, which provides a high-frequency current, and a high-frequency field; the field couples with
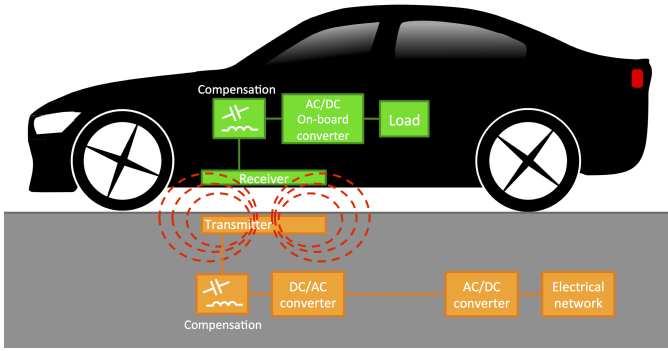
Fig. 2: General block diagram of an IPT system for electric vehicles.

Fig. 3: Cross-section of the buried transmitter and the on board receiver of the PATH prototype [12] (reprinted by permission).

the receiver, and allows the wireless transfer of electrical power. Downstream the receiver, a rectification stage converts the signal to dc, which allows the battery of the vehicle to be charged. In general, ferromagnetic, conductive and other auxiliary materials are added to the coils, and the ensemble is defined as a pad. Thanks to the absence of electrical contacts, the transmitter and receiver of an IPT system are independent. This feature can lead to the absence of external installations with the recharge process that can start automatically when the vehicle is over the transmitter, without any human interaction. This arrangement remarkably increases the safety of the operations, and reduces the possibility of vandalism. In addition, the system is inherently protected against environmental conditions (e.g. water, dirt, chemicals etc.). The absence of electrical contacts eliminates the typical problems of electrical erosion and dust deposition, reducing the maintenance costs and providing a more robust system with a longer life cycle. This technology, defined as static because the vehicle is parked during the charge, will most likely substitute the conductive systems. However, the absence of mechanical constraints opens to the possibility of the inductive transfer during the motion of the vehicle, which is the dynamic IPT. The installation of dynamic IPT systems into the road infrastructure would eliminate the necessity of stops for the vehicle charge and, consequently, lead to a possible reduction of the on-board battery capacity. A successful implementation of the dynamic IPT would improve the acceptance of electric vehicles, and solve the most critical aspects in their use. A third possible use of the IPT is the *stationary* or *en-route static* IPT, during which the charge takes place during the stops of the vehicle during the trip, e.g. the stops at the traffic lights. This case represents an intermediate way between the static and the dynamic IPT, as the vehicle alignment with the receiver cannot be accurate, however the vehicle position is practically stable.

A. The dawn of the power electronics

The first real application of the IPT arrived from the soviet electrical engineer George Iljitch Babat, who in 1943 built an electric car, named HF automobile supplied through IPT [7]. The system was composed by copper tubes buried under the asphalt, and a receiver placed under the vehicle at about 20 cm from ground. The system was supplied through an electron-tube oscillator [8] providing a current of hundreds of amperes with a frequency of 50 kHz. The induced current was rectified and used to directly supply a 2 kW motor. Babat adopted the capacitive compensation on both side of the circuit and proposed two techniques for the regulation of the power transfer based on the tuning of the capacitors and the variation of the shape of the coils. This prototype had only 4% efficiency, but it was the first working implementation of an IPT system for electric vehicles [4]. Babat patented the system after immigrating in the USA at the end of the Second World War [9].

The first IPT system with solid state devices appeared in 1974 [10], and it used thyristor inverters with a nominal current of 2000 A and frequency of 10 kHz. The resonance of the receiver was assured through series connected capacitors, and a rectifier supplied a dc motor. This design was abandoned in the same year [11]. In the 1980s, a complete working IPT system with a moving vehicle was designed within the project PATH in California [12]. The goal of the project was the development of a segment of an electric roadway to inductively power of a small electric bus. The system operated with a variable air-gap between 5 cm and 10 cm, and provided a power of 200 kW through a maximum current of 2000 A generated by an electric machine working at the fundamental frequency of 400 Hz. To control the power transmission, variable capacitors were employed to detune the receiver resonant frequency. The achieved efficiency was of about 60%, but the prototype presented different critical aspects, such as bulky and heavy pads: the receiver was 4.5 m long and 1 m large with a mass of 850 kg [11] (Fig. 3). In the 90s the massive interest of researchers and industries in the IPT technology started due to the improved performance of the power electronics devices at frequencies above the tens of kilohertz, with currents between tens and hundreds of amperes. At the end of the last century, the dissemination of IPT systems for the charge of hybrid and electric busses began. In 1997, the German Wampfler AG, implemented a first commercialized IPT system for public transportation based on patents developed by the Auckland University [13], [14]. This system was conceived to charge stationary busses, and the technology was commonly named static IPT. For the charge to be effective, the receiver needed be aligned with the buried transmitter, and lowered to the distance of about 4 cm (Fig. 4); to this purpose, a camera was placed under the vehicle. Electric buses wirelessly charged during parking, in a completely automated fashion, operate in Genoa and Turin since 2002 [15]. The Wampfler system is
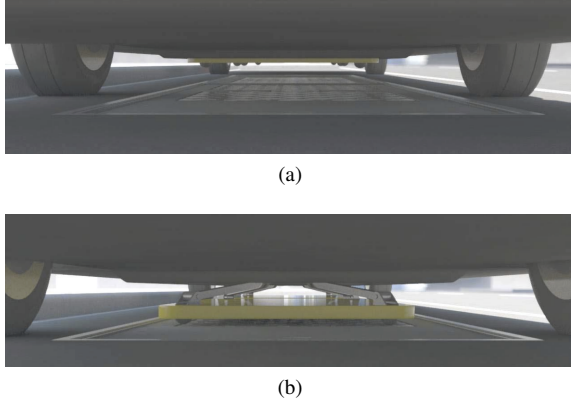
Fig. 4: Position of the receiver in the Conductix system. Receiver up (a), receiver down during the charge (b) [16].
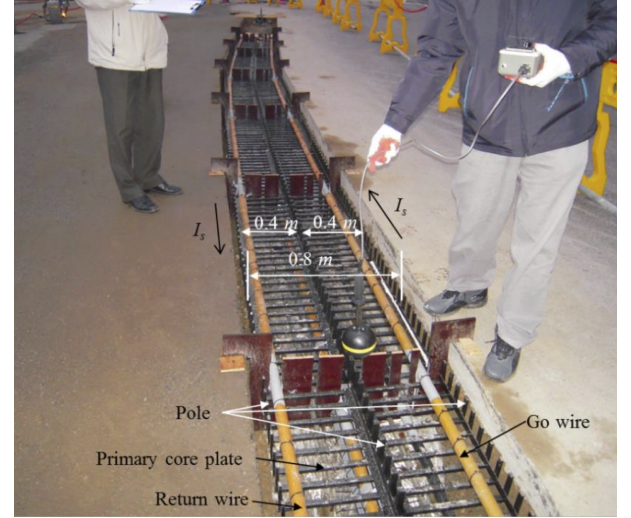

Fig. 5: Ferrite track of the OLEV system embedded in road [19] (reprinted by permission).

Fig. 6: Scheme of the architecture of the OLEV bus IPT system (adapted from [19]).

composed of two pair of transmitter and receiver operating at a frequency of about 20 kHz with a rated current of 80 A. Each pair of coils has a rated power of 30 kW allowing a power transfer of 60 kW. The small air-gap between transmitter and receiver guarantees a good magnetic coupling and reduced stray fields. Wampfler continued to work on these applications of the IPT as Conductix, and in January 2014 it spun off as IPT Technology.

III. STATE-OF-THE-ART

In the recent years, several companies and research centers have proposed their own systems to improve the electric mobility through the IPT. WAVE, a startup born within the Utah State University, commercializes its IPT technology for the recharge of electrical busses. The first prototype was implemented in a campus shuttle equipped with a receiver having the same dimensions as the transmitter embedded in the pavement of the bus stops. This system allows the transfer of 25 kW at 20 kHz at each bus stop. The power transfer takes place over an air-gap of $15 - 25$ cm obtaining an efficiency of 90% [17]. Bombardier has recently announced the development of a suite of solutions for IPT involving busses, light commercial vehicles, and private cars called PRI-MOVE. The implementation of the PRIMOVE IPT system for electric busses is ongoing in the cities of Mannheim and Berlin (Germany), and in the city of Bruges (Belgium). With this system, the transferring to the bus of a power of about 200 kW occurs during its stop [18]. The only working dynamic IPT system currently operating is the shaped magnetic field in resonance (SMFIR) system developed by the Korea Advanced Institute of Science and Technology (KAIST) since 2009. The SMFIR concept is based on the use of a massive quantity of ferrite to confine the flux into a defined path (Fig. 5). This concept was applied to the OLEV (online electric vehicle) bus in 2011 and, currently two OLEV busses are active in the KAIST campus in the cities of Daejeonn and Gumi, both in South Korea [20]. As shown in Fig. 6, the system is composed by a roadside power conversion stage that rectifies the power received by the electrical network and supplies the buried power tracks (i.e. transmitters) at the frequency of 20 kHz. The road embedded power tracks are installed in sections of
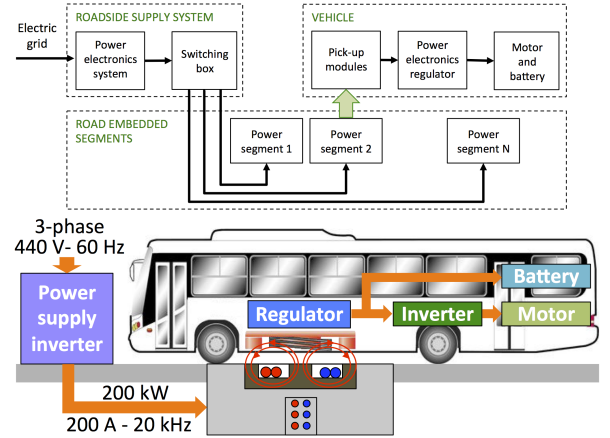
122.5 m in length, and each section is divided into segments, whose length can range from 2.5 m to 24 m [20]. A system of complex active and passive shielding solutions is installed on the bus, with the purposes of confining the magnetic field along the desired path, improving the electromagnetic compatibility (EMC), and reducing the electromagnetic field emissions. An example of shielding system is depicted in Fig. 7, where a series of copper twisted brushes is used to create a closed conductive shielding path [21]. KAIST developed different versions of OLEVs. The versions 3G and 4G reached a maximum power transfer of about 200 kW with an efficiency of 74% [22]. In the automotive sector several products for the static IPT will be soon available in the market. In 2011, Qualcomm acquired HaloIPT, a New Zealand company spun off by the University of Auckland. The HaloIPT developed IPT solutions in a power range between 3.3 kW and 20 kW, and in 2011 became partner with Rolls Royce, which proposed the IPT technology to charge the luxury Phantom EV [23]. A spin off of the Massachusetts Institute of Technology (MIT), WiTricity, that develops wireless power transfer systems for
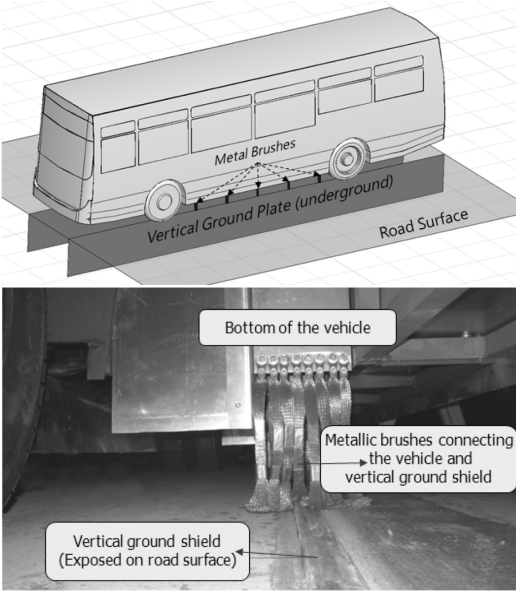
Fig. 7: Illustration of a passive shielding solution applied to the OLEV bus [21] (reprinted by permission).

Fig. 8: Picture of the laboratory prototype developed at ORNL [28] (reprinted by permission).

various industries and applications, also proposes a solution for the static IPT. Three systems at the power level of 3.7, 7.7 and 11 kW have been proven to be functional, but they are not yet commercially available [24]. However, Toyota has licensed the WiTricity wireless system and started trials and verification tests for their Electric and Hybrid models [25]. Another product available in the market is the Plugless Power, a 3.3 kW IPT stationary charger developed by Evatran and commercialized in partnership with Bosch. It consists of a system adaptable to each EV model, with a transmitter system composed of a control panel containing the power electronics directly linked into the electrical LV network, and a transmitter pad that can be placed on the floor. The Plugless Power were successfully tested with the Chevrolet VOLT and the Nissan Leaf EVs [26].

IV. RESEARCH PROJECTS

To respond to the necessity of additional investigations about the broad aspects of the dynamic IPT, dedicated research projects are being conducted thanks to both public and industry funding. While the University of Aukland and the MIT are trying to extend their static applications technologies to include the dynamic IPT with their spin offs HaloIPT and WiTricity, other research centers and universities are involved in joint projects all over the world. In the United States, the Oak Ridge National Laboratory (ORNL) is greatly investing in IPT research. The ORNL has carried out research on static and dynamic inductive power transfer, and is presently developing know-how on coupling coil design, power flow regulations, leakage field minimization, misalignment tolerance and interoperability [27]. The ORNL focuses on the use of a single power electronics stage that supplies the different transmitters (as done by the KAIST), determining the relative position of the vehicle by a radio communication

system coupled with optical sensors as backup verification. Transmitters and receiver coils are constituted by the same circular pad [28] (Fig. 8). At the same time, the KAIST is developing the sixth generation of OLEV, by improving efficiency with new solutions for the transmitter section layout and the design of the receiver [29]. In the European Union, a series of research project are being founded to investigate possible improvements of the electric mobility by developing solutions for the inductive charge. The projects Fastincharge and UNPLUGGED, both born in 2012, have investigated the impact of different charging solutions (i.e. plug-in, static and dynamic IPT) on the public acceptance of the electric mobility. In both projects different solutions for the static inductive charge have been proposed, based on economic feasibility, safety and standardization; an analysis of the expansion of these solutions toward the dynamic IPT was also performed [30], [31], [32]. Both projects demonstrated a good efficiency about 90% of two different static IPT solutions in condition of perfect alignment between transmitter and receiver together with the communication between the different components of the charging infrastructure. These results indicated as the use of IPT can really represent an effective way to overcome the actual problems related to range and size of the on-board storage.

At the end of 2012, the eCo-FEV project began [33]. eCo-FEV intended to create an electric mobility platform for the integration of electric vehicles into a cooperative infrastructure. This platform would allow the communication between multiple infrastructure systems, including road IT infrastructure, parking infrastructure, public transportation operators and vehicle charging infrastructure; this would assist user on trip planning, decreasing range anxiety (i.e. the fear that the electric vehicle has insufficient power to reach its destination). The results of the project proved the functionality of the proposed architecture for the integration of the EVs into different infrastructures, to create a cooperative network capable to provide precise telematic services, and charging management service based on real time data.

In Spain the researches on the IPT are continuing through the project Victoria [34]. The project started in 2013 with a consortium that comprises different industrial and academic partners. The aim is to double the range of electric buses without affecting operating times adopting IPT in static and dynamic developing a solution directly applied on a bus in the city of Malaga.

A summary of the parameters of the cited IPT systems is reported in Table I.

V. STANDARDIZATION PROCESS

IPT systems, as electric vehicles, involve several fields of engineering, therefore the related technical standards and guidelines must include many different view points. As pointed out in the previous section, several commercial stationary IPT technologies exist, but most of them are not compatible with each other, due to the absence of standards when they were developed. Nevertheless, there are several active groups working now to standardize stationary wireless charging systems. The U.S. Society of Automotive Engineers (SAE International), a globally active professional association and standards organization for engineering principally focused on transport industries, provides the standards SAE J2954 and UL 2750 [38], and pairs them to other related standards as SAE J2847/6, SAE J2931/6 and SAE J2836/6 [39]. SAE published a Technical Information Report (TIR) J2954 for *Wireless Power Transfer for Light-Duty Plug-In/ Electric Vehicles and Alignment Methodology* for stationary charging applications on 2016 that is planned to be standardised within 2018 [40]. The International Electrotechnical Commission (IEC) has created in the 90s the subcommittee TC69 that is working on a dedicated standard for electric vehicles equipped with IPT systems, which is intended to be published as IEC 61980. The IEC 6190 reached the Committee Draft stage in 2000 and, since 2013 the standards has been in a "circulated as committee draft with vote" phase [16] and his "Part 1: General Requirement", is now in the Publication being printed (BPUB) state [41]. ISO started his activities on a new ISO standard, the ISO/AWI PAS 19363, in February 2014 [42]. The group responsible for the drafting is subcommittee TC22/SC2 "Road Vehicles-Electrically propelled Road Vehicles" [43]. The main activities of the different standardization committees can be summarized as follows:

- vehicle alignment methods;
- interoperability of the different solutions;
- frequency and power levels;
- location of the receiver or receivers in the vehicle;
- different aspects of safety, such as obstacle detection, electric shock protection, reference standard for the magnetic field levels, EMC;
- communication protocols between power grid, vehicle and IPT infrastructure;
- testing of the solutions.

Despite the fact that IPT technologies evolve very fast, there are no published standards on IPT for automotive applications at the present. The same is also true for dynamic IPT. On this aspect, the IEEE Standards association industry connection

Fig. 9: First prototype of a dynamic IPT system for a light commercial vehicle within the eCo-FEV project (Italy).

activity has recently approved a working group for the pre-standardization, with the goal to be a complement to the activities of the SAE J2954. This is currently the only group working on dynamic IPT [44].

VI. A PROPOSAL FOR AN INTEROPERABLE DYNAMIC IPT

Starting within the eCo-FEV project, the team of the Department of Energy of the Politecnico di Torino, Italy, developed a first prototype for the dynamic IPT for a light commercial vehicle consisting of five transmitters installed in cable wireways placed over the road (Fig. 9) supplied by a single six-pole inverter [45]; the vehicle presence was identified solely through optical sensors. This system has been tested only for a limited power and limited speed, but has provided important data regarding the management of the charging infrastructure in the presence of a complex environment, which includes electric vehicles, energy providers and data infrastructure [46]. The goal of the research activities of the POLITO group is the development of an IPT solution applicable to light commercial vehicles. The target is private transportation companies that interact with public urban infrastructure as well as private charging spots. The system is oriented to the large scale market and includes a data infrastructure for the communication and management of the billing. This research is now continuing under the FABRIC project [47], [48]. FABRIC started in 2014 as a systematic feasibility analysis of different on-road charging technologies for the range extension of electric vehicles. The architecture developed by the team of the Politecnico di Torino in the framework of the project, called charge while driving (CWD), is shown in Fig. 10. It consists of a series of 50 transmitters 1.5 m long and 50 cm large with an interspace of 50 cm. In contrast with the solution proposed within eCo-FEV, in the FABRIC system, each transmitter is supplied by a dedicated dc/ac H-bridge converter. The POLITO CWD system has included the installation of the electrical equipment in an existing full-electric light commercial vehicle, without modifications to the vehicle chassis. The vehicle characteristics have been used to identify a proper power rating of the IPT system capable of matching the power consumption within a reasonable speed. This evaluation has been conducted according to a dynamic model similar to that proposed in [49], assuming the vehicle moving in the absence of road slope and at constant speed (see Section VI-C). A rated power of

TABLE I: Summary of the main parameters of cited IPT systems.

| Technology provider	Application	Rated power (kW)	Frequency (kHz)	Air-gap (mm)	Maximum efficiency	Reference
IPT technology	Buses (static)	60 kW (30 kW/trans.-rec. pair)	20 kHz	40 mm	90%[a]	[35]
WAVE	Buses (static)	$25 - 50$ kW	20 kHz	$15 - 25$ cm	90%[b]	[17]
Bombardier (PRIMOVE)	Buses (static and dynamic)	200 kW	N/A	N/A	N/A	[18]
KAIST (OLEV 3G)	Buses (dynamic)	200 kW (20 kW/receiver)	20 kHz	$10 - 20$ cm	74%[b]	[22]
Halo IPT	Cars (static and dyn. in future)	$3.3 - 6.6 - 22$ kW	85 kHz	$125 - 175$ mm	95%[d]	[36]
WiTricity	Cars (static)	$3.6 - 7.7 - 11$ kW	N/A	$10 - 15$ cm	94%[a]	[24]
EVATRAN (Plugless)	Cars (static)	3.3 kW	19.5 kHz	100 mm	88.8%[b]	[26]
CIRCE/Endesa (UNPLUGGED project)	Buses (static)	50 kW (25 kW/trans.-rec. pair)	25 kHz	25 cm	N/A	[31]
ORNL	Cars (dynamic)	2.2 kW	23 kHz	100 mm	75%[c]	[37]
Politecnico di Torino (POLITO CWD)	Light commercial vehicles and cars (dynamic)	20 kW	85 kHz	$10 - 25$ cm	91%[c]	

[a]Info about measurement points not available.　　[c]AC/DC output to AC/DC on board output.
[b]AC grid to battery input.　　[d]Coil to coil.
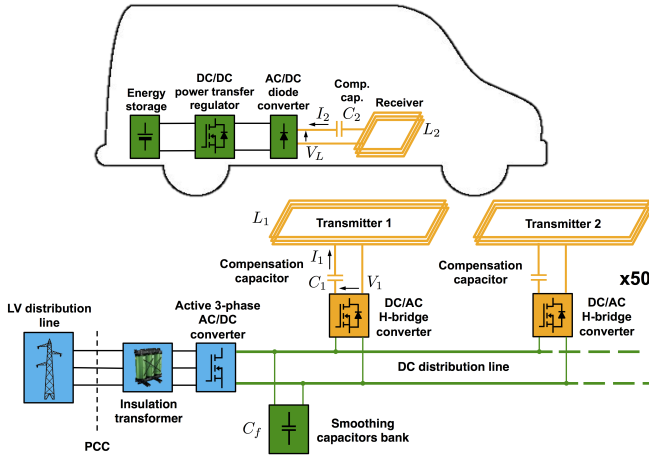
Fig. 10: Electrical infrastructure for the dynamic IPT proposed by the team of the Politecnico di Torino.

20 kW has been chosen for each single dc/ac converter of the IPT system. This power level is sufficient to match the power consumption of the adopted vehicle up to about 70 km/h in condition of perfect lateral alignment with the transmitter. In the following sections, each component of the system is discussed in more details.

A. Magnetic structure

The shapes of the transmitters present in literature are fundamentally of two typologies: the long track coil and the small coil of the same dimension of the receiver. The principal advantage of the long track coil consists in a continuous power transfer as the vehicle moves along the track. The track can be energized when the vehicle is over the coil using a unique source converter. In addition, if the size of the coil is sufficiently long, the detection of the vehicle does not need to be extremely precise and fast [50]. However, as the

dimension of the transmitter is much longer than the receiver, the long not coupled section of the coil causes the presence of a strong stray field. The stray field can represent a problem in terms of electromagnetic compatibility with the electronics devices on board, but also an important problem in terms of electromagnetic exposure of persons in the vicinity of the vehicle [51]. Structures with small transmitters reduce these problems, but sacrifice a continuos power transfer, and demand a very fast and precise system of detection of the vehicle [52]. A compromise solution has been implemented in the POLITO system. It consists of the adoption of long transmitters whose dimensions allow that each coil, when energized, is completely covered by the body of the vehicle also in conditions of misalignment. Another important difference with respect to the majority of previous works lies in the use of ferrite limited only to the receiver structure. The rationale behind this choice is the reduction of the overall costs of the system, as also suggested in other recent works [53], [54]. The elimination of ferrite increases the efficiency of the road pavement maintenance, and the robustness of the solution against vibration. As a secondary remarkable advantage, the absence of ferrite helps maintain a low value of self-inductance in relation to the considerable length of the coil. The transmitters have been buried at 5 cm below the road pavement. When a transmitter is active and supplied with the nominal current, the inter-distance of 50 cm guarantees an effective coupling with the non-active transmitters present in the vicinity, which generates an induced open-circuit voltage less than 30 V. This voltage does not create problems to the dc/ac converter and it is perfectly manageable during the start-up phase.

Among the different possibilities, e.g. [36], [55], a simple rectangular shape has been chosen for the receiver coil, as this shape is simple and tolerant to misalignment [56], [57]. The coil is part of a structure (Fig. 11) designed and optimized so that to maximize the coupling and minimize the stray field outside the vehicle: this to be in compliance with the ICNIRP
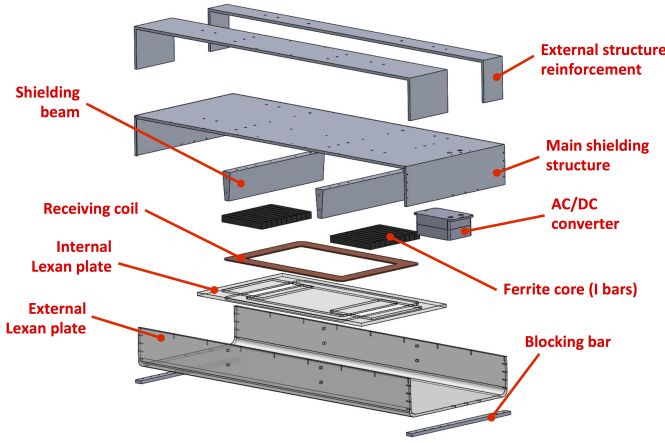
Fig. 11: 3D model of the receiving structure.

restrictions on human exposure [58], [59]. This structure therefore also plays the role of an electromagnetic shield, whose purpose is to confine the magnetic field in a defined volume under the vehicle. The receiving structure is mounted on the rear of the vehicle with the addition of supports to guarantee mechanical robustness and protection against vibrations. The dimensions of the receiver have been chosen through an optimization process with the goal to obtain a certain values of mutual inductance ($14.3\ \mu$H in rated conditions) with a reduced length in the direction of the movement. In fact, a shorter receiver means a longer period of constant coupling and constant transferred power during the movement. In nominal conditions, the distance between the buried transmitter and the receiver equals 25 cm. The related values of self-inductance are $280\ \mu$H for the transmitter and $120\ \mu$H for the receiver. These values are weakly affected by the vehicle position due to the considerable distance between the coils, the distance of the vehicle chassis and the absence of ferrite in the transmitter side. The movement does not influence the receiver inductance while the value of the transmitter inductance has a variation of less than 3%. This stability reflects also in the coil coupling. In condition of misalignment, the system is able to transfer a reduced power up to a lateral misalignment of 30 cm which means a coupling coefficient of about 0.05.

B. Supply side and power electronics

The series of dc/ac converters is supplied through a dc distribution line that constitutes the dc bus of the overall IPT system. Particular attention has been devoted to the protection of persons against the risk of electric shock. In the case of ground-faults, in fact, stray currents may circulate and energize the underground conductors. This condition is potentially harmful for operators working along the ground tracks. For this reason, the system is connected to the LV distribution system by means of a Class II insulating transformer (i.e. protected by at least two layers of insulation between primary and secondary sides), which electrically separates the utility three-phase distribution system from the IPT, allowing a dedicated IT system [60]. This solution guarantees the continuity of the power supply also after a first ground-fault

without compromising the safety of the operators. The IT grounding system was chosen as the protection against indirect contact in TN systems[1] [60] is challenged by the presence of active converters. In the case of ground-faults, in fact, converters positively reduce the fault current to nearly their nominal current, to protect their circuitry. This limitation of the current would prevent overcurrent protective devices from promptly tripping, exposing persons to the risk of electric shock. It is worth noting that some national and international standards specify a minimum burying depth for cables under streets, highways, roads, alleys, driveways, and parking lots (the National Electrical Code (NEC) requires, for example, 60 cm [61]). However this requirement might be satisfied only by the distribution cables and not by the transmitting coils. A solution where all cables are Class II (i.e. double insulated) [62] is adopted. Hazardous conditions still exist for road workers operating on the road when the charging station is active. To ensure safety, the charging area must be considered as a live working zone and operators must be suitably trained.

A three-phase ac/dc converter provides for a 630 V stabilized dc distribution line that supplies the dc/ac (i.e. direct current to high frequency alternate current) converters forming a distributed dc link. The rated power of transformer and ac/dc converter has been chosen equal to 50 kVA as a way to test the condition of two vehicles moving over the equipped charging lane at the same time. The distance between the coils is set such that during the vehicle motion there is a time interval when the receiver is not coupled with any transmitter. This solution allows a simpler procedure of activation of the right transmitter together with the identification of the presence of the vehicle over the coil. However, the passage of the vehicle from one transmitter to the next can generate an abrupt variation of the absorbed power, causing stress at the point of common coupling (PCC) with the utility network. This stress may cause degradation of the power quality due to possible voltage fluctuations. To mitigate this problem, the introduction of a capacitive smoothing made of super capacitors is proposed as similarly done in [28], [37]. The aim of the capacitors bank is to maintain constant the current at the output of the ac/dc converter thereby reducing the harmonic content at the PCC. The value of the capacitance has been fixed at 2.6 F as result of the analysis presented in [63].

The adopted dc/ac converters power each transmitter by using a fixed frequency control technique. The operating frequency has been chosen equal to 85 kHz in order to keep the compliance with the SAE standard J2954 as a base for future interoperability between static and dynamic systems. The developed power electronics has been presented in [64].

Aboard the vehicle, a dc/dc converter is connected between the diode rectification stage and the battery to effectively manage the power being received. The discontinuity in the coupling during the passage from one transmitter to a subsequent one, can mirror in a discontinuous charge of the EV

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[1]Systems in which the neutral point of the power supply system is grounded, and enclosures of equipment are connected by a protective conductor to the main grounding bus of the installation, which is connected to the grounded point of the power supply.

TABLE II: Main parameters of the POLITO CWD system

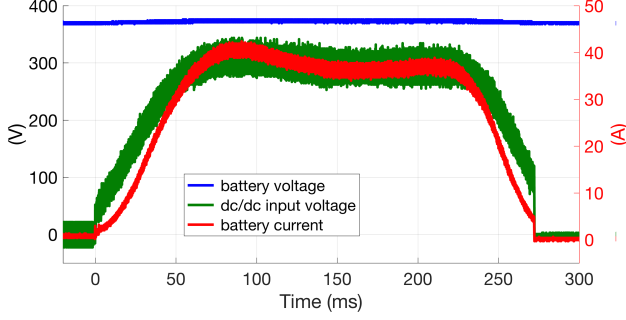| Parameters	Value
Rated power	20 kW
Rated frequency	85 kHz
Rated DC primary voltage	630 V
Transmitter current	36 A
Receiver current	75 A
Transmitter inner dimensions	0.5 m × 1.5 m, 10 turns
Receiver inner dimensions	0.53 m × 0.3 m, 10 turns
Coil-to-coil distance	0.5 m

Fig. 12: Waveforms registered on board during the passage over a transmitter at a speed of about 20 km/h. The maximum power delivered to the battery is 15.9 kW.

battery. This fluctuation could be managed, for example, with the addiction of a capacitive smoothing also in the receiver side [28].

The main parameters of the POLITO CWD system are summarized in Table II. In Fig. 12 are presented the waveforms of some on board quantities registered through an oscilloscope during the passage of the vehicle over a transmitter at the speed of about 20 km/h and in absence of control of the alignment.

C. On road installation

The final appearance of the implemented charging lane is shown in Fig. 13. The transmitters are embedded under the road pavement and the electrical and mechanical integrity of the coils are protected by means of a specific developed embedding methodology (herein not detailed) The terminals of two consecutive transmitters reach a manhole placed in the vehicle side where two dc/ac converters are placed. The manhole is also the point of connection between the DC distribution line and the converters by means of an in/out configuration. This line follows a path at 60 cm under the ground together with an auxiliary ac distribution at the standard level of 230 V, 50 Hz. The line is connected with a shelter where are placed the transformer, the ac/dc converter and the capacitors bank. According to the representation of Fig. 14, the charging unit is used as reference for the estimation of the costs of the implementation of the charging lane that are summarized in Table III. The resulting cost has been of about 558 €/m. As well, the basic unit can be used to estimate the percentage of road that has to be equipped in order to guarantee a stable state of charge of the battery with respect to different constant speeds of the vehicle. This evaluation can be conducted considering each basic unit as delivering the rated
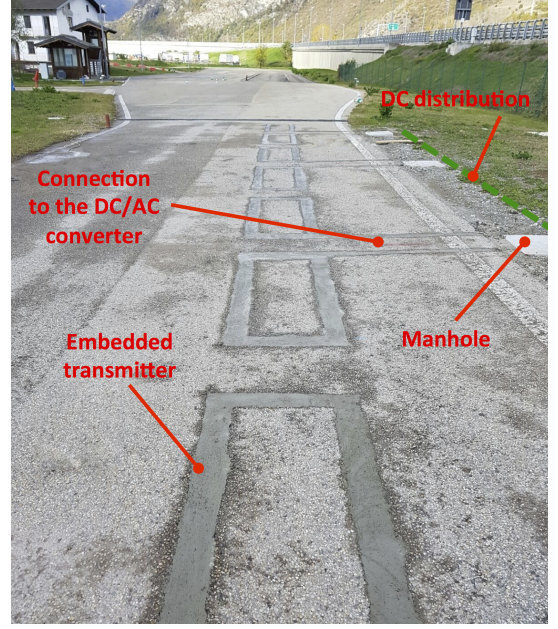

Fig. 13: Final aspect of the charging lane installed in the road infrastructure.
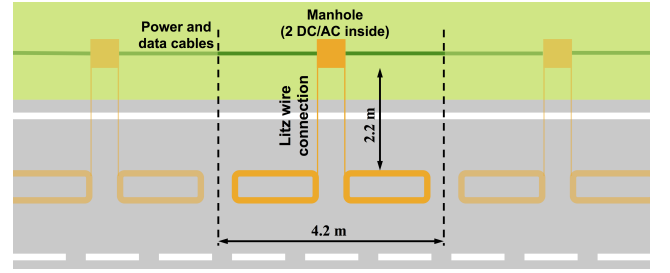

Fig. 14: Scheme of a charging unit considered for the estimation of the cost per meter.

power of $P_r = 20$ kW and estimating the self consumption of the vehicle P_{ve} according to the steady-state model:

$$P_{ve} = \frac{1}{\eta_{tr}} \left(mgC_r v + \frac{1}{2} \rho A_f C_x v^3 \right) \qquad (1)$$

where m is the mass of the vehicle, g is the gravitational acceleration, ρ is the air density, v is the speed of the vehicle and A_f is the frontal area. C_r and C_x are the rolling resistance coefficient and the drag coefficient, respectively. For the adopted vehicle the values of these parameters are

TABLE III: Charging unit components and costs.

| Description	Quantity	Cost
DC cables	4.2 m	15.00 €
Data and auxiliary supply cables and pipes	4.2 m	8.00 €
Manhole	1	20.00 €
Power and data connectors	1	40.00 €
Transmitter and comp. capacitors	2	500.00 €
DC/AC converter	2	600.00 €
Materials for transmitter embedding	Lump sum	300.00 €
Manpower for DC line and manholes placing	Lump sum	320.00 €
Manpower for transmitters embedding	Lump sum	540.00 €
Total cost		**2343.00 €**
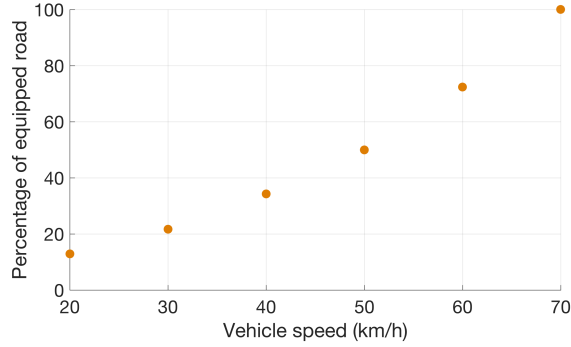
Fig. 15: Percentage of road equipped with the POLITO CWD charging unit (orange) able to maintain stable the battery state of charge.

$m = 3500$ kg, $A_{\mathrm{f}} = 3.8$ m^2, $C_{\mathrm{r}} = 3.8$ m^2. The value of the rolling resistance coefficient is dependent on the vehicle speed and the typology and conditions of tires and road pavement. In the proposed case the value of this coefficient is practically constant and equal to 0.015. The efficiency $\eta_{\mathrm{tr}} = 0.8$ is added in order to take into account the efficiency of the power train. The percentage of the equipped road at different speeds is obtained as $P_{\mathrm{ve}}/P_{\mathrm{r}}$ and shown in Fig. 15.

VII. Conclusions and open issues

This work is based on [65]. Static inductive power transfer is a mature technology that most likely will be widely used for automotive applications. The lack of electrical contacts makes the system more reliable and non-invasive in urban contexts. Dynamic IPT is an interesting improvement of the IPT: the massive use of electrified road infrastructure may change the perception of the user about the electric mobility, improving the market penetration thanks to an extended battery autonomy.

However, the dynamic IPT is still under development and many challenges are still unsolved:

- different answers have been provided for the sizing of the pads, with opposite solutions: long track transmitters (in the order of hundred meters) [66] coexists with the use of small circular pads [37] as well as overlapping coils [55];
- the integration and durability of the on-road infrastructure is unknown and may interfere with the typical road lifetime;
- the power levels and frequency range, which affect the choice of power electronics components, are still under discussion;
- the effects of the electromagnetic bursts on the electronic on-board components as well as the compliance with the ICNIRP recommendations for human exposure must be evaluated during the entire charging phase [67], [68], [69];
- different techniques for the vehicle detection and identification when approaching the charging pads as well as the handoff between consecutive coils are under investigation, such as the use of auxiliary coils [70], [71], optical

sensors, radio or wired communications [37] between the power electronics;
- The detection of foreign objects close to the charging lane is a critical issue [72]. Magnetic and conductive bodies could, in fact, modify the shape of the magnetic field, heat up under the effect of induced currents and affect the performance of the system, as well as the safety of the space in proximity of the energised parts [73].

As detailed in this paper, many actors are working on different solutions to these problems, with possible conflicting outcomes. The standardization process is in its early stage, however the general trend is to replicate procedures and standards from the static IPT in order to enforce the interoperability between the static and dynamic systems. Despite the uncertainty surrounding the dynamic IPT, it looks promising as confirmed by the numerous private and public investments in this field. The final penetration into the market is however limited by the high costs of the road infrastructures, which requires investments by public institutions and governments.

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