Wireless power transfer structure design for electric vehicle in charge while driving

Wireless Power Transfer Structure Design for Electric Vehicle in Charge While Driving

Vincenzo Cirimele, Fabio Freschi *Senior Member IEEE*, Paolo Guglielmi *Member IEEE*
Politecnico di Torino, Department of Energy
Corso Duca degli Abruzzi, 24, 10129 Torino, Italy
vincenzo.cirimele@polito.it

***Abstract*—In the last years the interest on the inductive charging of electric vehicles is grown according to the increase of the electric vehicle market. In this paper a novel approach to the design of a charge while driving wireless power transfer structure is proposed with several improvements with respect to the previous works on the same topic. Different suitable solutions are analyzed and a new hybrid topology for the capacitive compensation is proposed. The rules to correlate the real system with a down-scaled model are given and applied to a scaled wireless power transfer prototype used to validate the proposed theoretical approach.**

***Index Terms*—Air gap - Charge while driving - Circuit simulation - Coupling circuits - Electric vehicles - Inductive power transmission - Mutual coupling - Power MOSFET - Resonant inverters - Wireless power transmission**

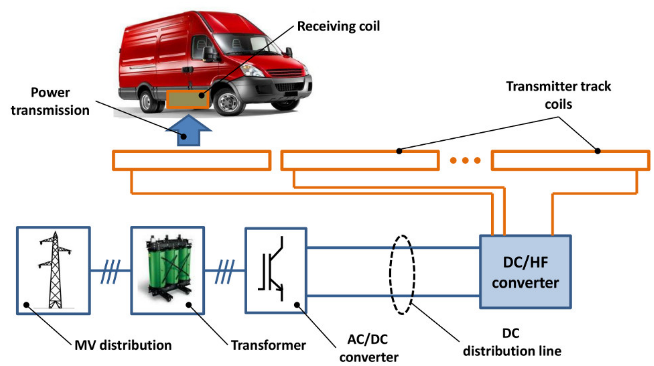

Fig. 1: Functional representation of the proposed CWD system.

I. Introduction

THE interest in the Wireless Power Transfer (WPT), also known as Inductive Power Transfer (IPT), is grown in the last years according to the development of the electric vehicle (EV) market. Many EV manufacturers have shown their interest into the wireless charging of electric vehicles with a large number of studies and prototypes. The static wireless charging is now a mature technology proposed by different manufacturers and many functional solutions have been developed and currently marketed [1], [2], [3].

Nevertheless, the research in the wireless power transfer is moving towards the so called Charge While Driving (CWD). The goal of these system is to extend the battery range of an EV by a fast and partial charge during the movement of the vehicle.

The aim of this paper is to preliminary prove the feasibility of a WPT system that will be the base for the future development of the CWD system for a light commercial electric vehicle during the motion along an electrified road.

Many researchers propose the use of a multiple installation of the elementary charging unit used for the static charge [4], [5], [6], [7]. Others prefer to adopt a different arrangement with long track coils under the ground level [8], [10]. The solution introduced in this paper chooses an intermediate approach adopting a series of track coils with dimensions comparable with the vehicle's length and a pick-up coil mounted under the vehicle platform. The architecture is shown in Fig. 1. A further key point of the proposed solution is the high voltage power transmission and the relative low value of current at the inverter output. In previous works the power transmission is designed with an imposed constant current, whose value is chosen as the main design parameter [8], [9], [11], [12]. In the proposed structure the design parameter is the supply voltage amplitude. Consequently, the structure design must also face with the impedance matching in order to minimize the current required by the power electronic. In the present work, some circuital arrangements for this problem solution are proposed.

To provide a demonstration of what affirmed, a down-scale prototype has been realized after the study of precise rules for the down-scaling of this type of structures.

The paper is organized as follows. Section II briefly introduces the symbols and basic WPT coupling solutions. The definition of a suitable CWD-WPT solution together with the choices for the power electronic structure is reported in section III. A new circuital arrangement for the coupling coil compensation is presented in section IV. Down scaling rules, together with the realized prototype, are reported in section V. Section VI discusses experimental results and finally some concluding remarks are given in section VII.

II. Inductive wireless power transfer fundamentals

Each WPT system is based on the mutual coupling between a fixed transmitter coil and a moving receiver that can be well represented by the circuit of Fig. 2. The load resistor R_L is used to represent the equivalent input resistance of the battery and its recharge circuit [13]. The receiving side is

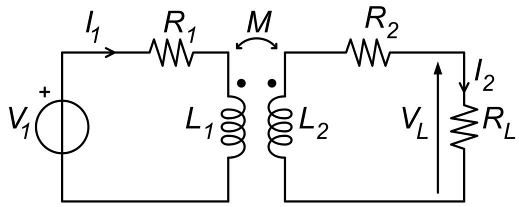

Fig. 2: Circuit model of coupled inductors.

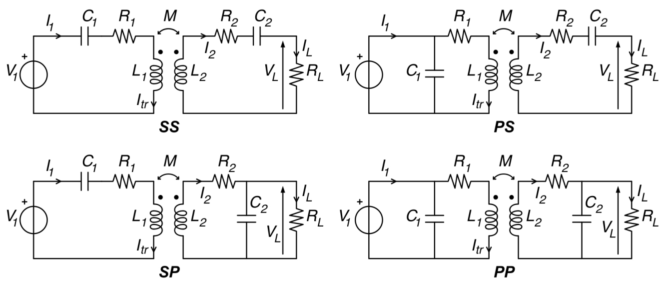

Fig. 3: Basic topologies for IPT compensation

characterized by the open-circuit voltage V_{oc} and the short-circuit current I_{sc} expressed as:

$$V_{oc} = \omega M I_{\mathrm{tr}} \tag{1}$$

$$I_{sc} = \frac{M}{L_2} I_{\mathrm{tr}} \tag{2}$$

The product of these two parameters gives information about the maximum power transmission capability of the IPT circuit.

Usually, these systems present a passive compensation of the inductive contributes in order to maximize the power transfer capability and to minimize the VA rating of the power electronics supply. This implies to obtain a resonant system and the possibility in the adoption of zero-voltage/zero-current switching techniques reducing ideally to zero the switching losses.

The basic topologies used for the compensation are shown in Fig. 3. Each scheme is referred to with two letters, indicating the type of compensation adopted for the transmitting and receiving coils, respectively. The letters S and P are used for the series and parallel compensation.

For each case, the transmitted power of a perfectly compensated system is expressed as:

$$P_2 = Q V_{oc} I_{sc} = \omega Q_2 \frac{M^2}{L_2} I_{\mathrm{tr}}^2 \tag{3}$$

where the parameter Q_2 is the quality factor of the receiving coil and its value depends on the secondary compensation topology:

$$Q_2 = \begin{cases} \dfrac{\omega L_2}{R_L} & \text{for series secondary compensation} \\[2ex] \dfrac{R_L}{\omega L_2} & \text{for parallel secondary compensation} \end{cases} \tag{4}$$

I_{tr} represents the current flowing in the transmitting coil directly responsible of the power transmission. In the case of a series compensation, it corresponds to the current of the source I_1.

Another important figure of merit of WPT systems is the total impedance Z_T, i.e. the impedance that the compensated structure shows to the power supply. Also this parameter is influenced by the compensation schemes, but for weakly coupled systems, its value is strongly depended by the selected primary compensation [9], [11], [14]. The analytic expressions of the total impedance are:

$$\underline{Z}_T^{SS} = R_1 + \mathrm{j}\omega L_1 + \frac{1}{\mathrm{j}\omega C_1} + \frac{\omega^2 M^2}{R_2 + R_L + \mathrm{j}\omega L_2 + \frac{1}{\mathrm{j}\omega C_2}} \tag{5}$$

$$\underline{Z}_T^{SP} = R_1 + \mathrm{j}\omega L_1 + \frac{1}{\mathrm{j}\omega C_1} + \frac{\omega^2 M^2}{R_2 + \mathrm{j}\omega L_2 + \frac{R_L}{1+\mathrm{j}\omega R_L C_2}} \tag{6}$$

$$\underline{Z}_T^{PS} = \left(\frac{1}{R_1 + \mathrm{j}\omega L_1 + \frac{\omega^2 M^2}{R_2 + R_L + \mathrm{j}\omega L_2 + \frac{1}{j\omega C_2}}} + \mathrm{j}\omega C_1 \right)^{-1} \tag{7}$$

$$\underline{Z}_T^{PP} = \left(\frac{1}{R_1 + \mathrm{j}\omega L_1 + \frac{\omega^2 M^2}{R_2 + \mathrm{j}\omega L_2 + \frac{R_L}{1+\mathrm{j}\omega R_L C_2}}} + \mathrm{j}\omega C_1 \right)^{-1} \tag{8}$$

III. Charge while driving and voltage supplied inverter power structures

One of the key points in the proposed WPT system for CWD is the simplification of the power electronic stage for the primary (transmitting) power converter.

The CWD mode of a WPT structure requires a solution in which multiple coils can be rapidly switched on and off, considering that the vehicle will remain over each transmitting module for a limited amount of time, depending on the vehicle speed.

In order to provide an adequate energy transfer with a minimum stray field, the emitter is made of rectangular coils as long as half the length of the vehicle. A unique power electronic structure can supply up to six transmitting coils moving from one coil to the following. With this approach, the receiving coil is illuminated by a continuous emitting field while passing from one transmitting coil to the other.

This arrangement creates a charging zone whose length depends on the number of coils each with its power electronics. The larger the number of coils, the larger the number of power electronics modules. Consequently, if standard power supply circuitry is adopted, cost, space and reliability of the system is a real issue.

The proposed high frequency distribution is made by a number of voltage supplied inverter legs equal to the number of coils plus one, all supplied by a common and stabilized high voltage DC-link as shown in Fig. 4. The proposed architecture is born to allow supplying more receiving coils (moving vehicles one near by the other) at the same time. More, the choice to have a direct control of each coil is due to the necessity to fast change the supplied coil in CWD:

at the speed of 40 $\mathrm{km/h}$ the permanence of the receiving coil over transmitting one is in the order of 100 ms, due to the adopted coil dimensions. An electromechanical device to switch from one coil to another is, this way, unreasonable. A solid state commutator can be adopted but it should have the same electrical characteristics of a H-bridge leg and it would be in series to the coil, than only increasing the converter losses.

A mosfet leg solution is proposed due to its linearity in the output voltage drop and to its fast switching capability. The whole structure is supplied at 600 V approx. in order to reduce the single switch current to less than 40 A (rms value) for a 20 kW maximum power transfer.

The proposed solution presents a reduced-size power converter without additional inductive components. All legs are controlled by a single controller that is able to manage the power distribution among the coils.

The appearance of the power converter for the full-scale prototype is depicted in Fig. 5. The proposed converter allows the test of the different possible compensation schemes, as described in the next sections.

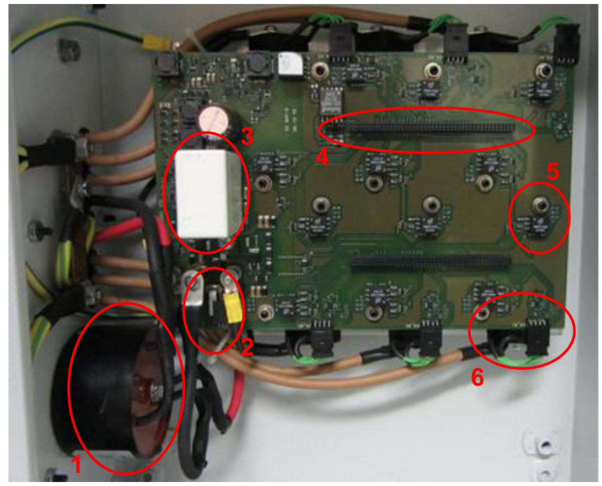

Fig. 5: Power electronic prototype for the final CWD-WPT system. 1. Current choke compensator 2. I_{DC} measure 3. DC smoothing capacitor 4. Connector to control 5. Switch command driver and supply 6. AC current sensor

IV. System design

As already mentioned in Section I, in a voltage supplied inverter oriented system, the value of impedance seen by each H-bridge acquires a relevant importance in order to predict the appropriate value of the current supplied by the power electronics devices.

Each topology is characterized by a different value of the impedance for equal parameters. PS and PP compensations show high impedance so they need a high and not manageable voltage source to transmit relevant power. On the opposite, SS and SP compensations show low impedance, as low as the WPT system is loosely coupled, so this means to have a very high value of the current especially if the system works with a high fixed voltage level. It is therefore clear that, in series compensated transmitting structures, it is important to obtain an appropriate value of the total impedance.

Considering the expressions (5) (6) of the total impedance for the SS and SP topologies, it is possible to note that the impedance matching is strongly dependent on the value of mutual inductance M and the operating angular frequency ω.

As mentioned in [11], [14], [17], [18], the SS compensation topology is to be preferred, because of the possibility to delete the effect of the coupling change during the motion on the resonance condition and according to the long dimension of the primary coil. In fact, the high value of the transmitter coil self-inductance means the generation of a high voltage drop not directly manageable by the power electronic without the use of the series capacitor. However, a parallel secondary topology can be selected in order to take advantage by the capability of this arrangement to provide a gain of the open-circuit voltage over the load.

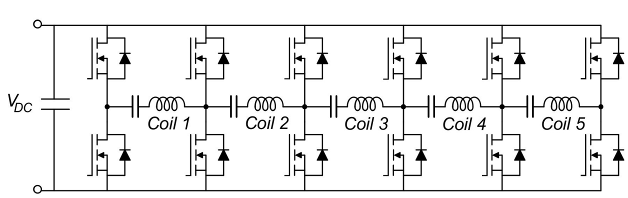

Fig. 4: Power electronic structure for a group coil in CWD-WPT solution.

The principal information required for the system design are here summarized:

- Vehicle geometry: these information influence the maximum dimensions of the receiving coil and the position with respect to the ground.
- Transferred energy per coil: this parameter is a trade-off between the transmitter length and the vehicle speed [15] and it influences the transmitter coil dimensions. The coil width is selected in order to maximize the coupling with the receiver. The limit to the transmitter length is represented by the maximum acceptable voltage drop that influences also the characteristics of the compensation capacitors.
- Rated voltage and current of the power electronics: these information control the choice of the total impedance and, consequently, the values of the electric parameters of the system.
- Current density: the selection of an appropriate value of the current density in the coil conductors depends on the cooling system. In the case where the cooling is obtained by natural air convection, the recommended value is in the range of 3-4 $\mathrm{A/mm^2}$. The current density influences the winding cross-section and the subsequent value of the self-inductance.

The switching frequency is used as a constant given value for the design in several works, but, it is possible to use the frequency as a parameter that can be modified during the design process [11]. In particular, in a SS compensated system, the frequency can be used to obtain a high value of the product ωM and the consequent Z_T.

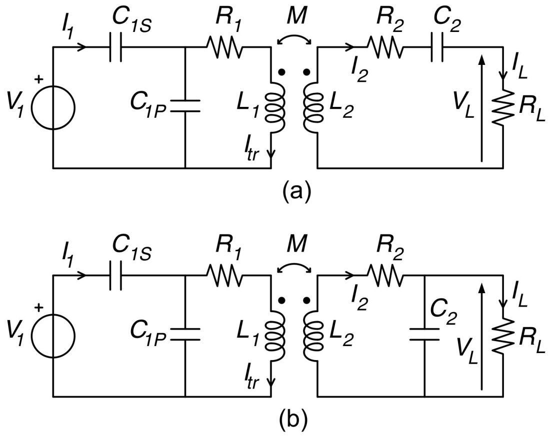

Fig. 6: Hybrid compensation topologies. SP-S (a) and SP-P (b)

A. The hybrid primary compensation

As already mentioned in the previous section, primary series or parallel compensated systems show a significant difference of the total impedance. Considering the same magnetic structure, Z_T^P is approximately one order of magnitude larger than Z_T^S. In fact, while a parallel LC resonant circuit can be assimilated to an open-circuit, the behavior of a series LC resonant circuit is equal to a short-circuit. Starting from these remarks, it is possible to think to combine the two topologies in order to obtain a structure having hybrid characteristics and presenting a Z_T that fits the needs of the power electronics.

A new design parameter α is defined as the fraction of the parallel primary capacitance C_1 calculated for the simple parallel primary compensation (PS or PP) and a related equivalent capacitance is assumed as $C_{1P} = \alpha C_1$. The series capacitance for this case is named C_{1S}. Clearly, if $\alpha = 1$ then $\frac{1}{\mathrm{j}\omega C_{1S}} = 0$ that is equivalent to a PS topology; if $\alpha = 0$ then $\frac{1}{\mathrm{j}\omega C_{1P}} \to \infty$ that is equivalent to a SS topology.

In order to maintain the resonance, the C_{1S} capacitance must compensate the exceeding reactive part of the equivalent impedance composed by the parallel between C_{1P} and the series of the L_1 and the imaginary part of the reflected impedance of the receiving coil on the primary side.

With reference to the circuit shown in Fig. 6, the total impedances are:

$$\underline{Z}_T^{SP-S} = \frac{1}{\mathrm{j}\omega C_{1S}} + \left(\frac{1}{R_1 + j\omega L_1 + \frac{\omega^2 M^2}{R_2 + R_L + \mathrm{j}\omega L_2 + \frac{1}{\mathrm{j}\omega C_2}}} + j\omega C_{1P} \right)^{-1} \tag{9}$$

$$\underline{Z}_T^{SP-P} = \frac{1}{\mathrm{j}\omega C_{1S}} + \left(\frac{1}{R_1 + \mathrm{j}\omega L_1 + \frac{\omega^2 M^2}{R_2 + \mathrm{j}\omega L_2 + \frac{R_L}{1 + \mathrm{j}\omega R_L C_2}}} + \mathrm{j}\omega C_{1P} \right)^{-1} \tag{10}$$

For an imposed purely resistive Z_T, it is possible to identify an adequate parameter α that satisfies all the conditions. In this way, the use of a series-parallel primary compensation (SP-S or SP-P) allows to decouple the two aspects of the impedance matching and the magnetic structure design. The latter can be designed considering only the maximization of the coupling and the design of secondary electrical parameters.

In addition, the hybrid primary compensation introduces other benefits as:

- distributing and mitigating the electrical stresses over the capacitors;
- reducing the ESR capacitor power losses;
- taking advantage by the intrinsic characteristic of the parallel resonator to be intrinsically protected from the short circuit current.

Despite of these advantages, the hybrid compensation can generate problems to the resonance control and commutations, caused by the possibility of the presence of sub-resonance phenomena established between the parallel capacitance and the parasitic inductance of the link-conductors between the power electronic and the coil. To reduce these effects it is recommended to place the power electronic close to the magnetic structure, minimizing the effect of the self-linked flux that causes the parasitic inductive effects. An example of the effect of these sub-resonance phenomena is shown in Fig. 12 of Section VI where a real system is analyzed. If the current tolerable by the power electronic is relatively high, the needed value of the total impedance is then low and easily suitable through an increasing of the mutual inductance or frequency, it is advisable to use a pure series compensation: in fact the value of the needed parallel capacitance, in this case, becomes very small and the advantages of the hybrid compensation are negligible respect to the introduction of an other component and the probably problems related to the sub-resonance phenomena.

V. Down-scale model

In order to provide a verification of the previous considerations, a down-scale model of the real system has been realized. It is important to know the relations between the scaling factor of the magnetic structure and other electrical parameters in order to obtain useful information for the real system evaluation.

The relations that allow to realize a scaled model are obtained assuming a constant current density J in the conductors and keeping the frequency at a constant value. In other words, it is assumed the same material exploitation and the same switching frequency of the power electronics devices. The first hypothesis can be sustained by the use of appropriate litz wire that allows to mitigate the skin and proximity effects. In the following analysis, a scaling-factor k is used for all linear dimensions. Assuming a linear behavior of the materials, the relations between the linear dimension and the electromagnetic parameters are:

$$\mathcal{R} = \frac{l}{\mu S_{mgn}} \propto \frac{1}{k} \tag{11}$$

$$L, M \propto \frac{N^2}{\mathcal{R}} \propto k \tag{12}$$

$$R = \rho \frac{l}{S_{wire}} \propto \frac{1}{k} \tag{13}$$

Where $\mathcal{R}$ is the reluctance of the magnetic circuit, L and M are the self and mutual inductance, R the resistance of a generic coil and S_{wire} and S_{mgn} are the cross section of the conductor and the equivalent section of the generic magnetic circuit.

Under the assumption of a constant current density, the system currents are scaled as:

$$I = JS_{wire} \propto k^2 \tag{14}$$

The transmitted power, defined in (3), is proportional to the product $V_{\mathrm{oc}}I_{\mathrm{sc}}$, thus:

$$V_{\mathrm{oc}} = \omega M I_{\mathrm{tr}} \propto k^3 \tag{15}$$

$$I_{\mathrm{sc}} \propto k^2 \tag{16}$$

$$P_2 \propto k^5 \tag{17}$$

Neglecting the losses, the transmitted power supplied by the power electronics, out the losses, is:

$$P_{\mathrm{source}} \propto P_2 \propto k^5 \tag{18}$$

Equations (14) and (18) imply that the supply voltage V_1 and the load voltage V_L are proportional to k^3. From the scaling relations obtained so far, it follows that the load scales is:

$$R_L \propto \frac{V_{\mathrm{L}}^2}{P_2} \propto k \tag{19}$$

These information can provide also an indication on the efficiency of the real system. In fact, it is clear that the power losses in the conductive and in the ferromagnetic materials depends on their respective volumes, thus the dependence of total power losses P_{loss} on the linear dimension is expressed as:

$$P_{\mathrm{loss}} \propto k^3 \tag{20}$$

Equations (17), (18) and (20) show that the real WPT system is more efficient and lighter than its down-scaled model:

$$\eta = \frac{P_2}{P_2 + P_{\mathrm{loss}}} \propto \frac{k^5}{k^5 + k^3} \tag{21}$$

Starting from these relations, a down-scale prototype of a 20 kW WPT system was assembled as shown in Fig. 7. Using a scaling coefficient $k = 0.4$, the prototype characteristics are summarized in Table I. The rated frequency is chosen equal to 85 kHz as prescribed by the U.S. standard in wireless power transmission that indicates this value with a range of ± 2.5 kHz [16].

Fig. 7: Down-scale prototype.

TABLE I: Down-scale prototype parameters

Parameter		**Value**
Transmitter dimensions		10×75 cm
Transmitter inductance	L_1	86 μH
Transmitter number of turns	N_1	9
Transmitter resistance	R_1	350 mΩ
Primary series capacitance	C_{1S}	41 nF
Receiver dimensions		25×20 cm
Receiver inductance	L_2	84 μH
Receiver number of turns	N_2	12
Receiver resistance	R_2	300 mΩ
Secondary series capacitance	C_2	42 nF
Air-gap		10 cm
Rated supply frequency	f_0	85 kHz
Rated bus voltage	V_1	40 V
Load resistance	R_L	2 Ω

VI. Experimental Results

The first test, performed on the prototype presented in Section V, examines the behavior with a SS compensation. Fig. 8 and Fig. 9 represent respectively the real and the PSpice simulated system: they show that the simulated model reflect correctly the real behavior. It is worth noting that the exact resonant condition is not achieved: this depends by the first rough control that determines an effective switching frequency at 83.3 kHz. This not exact resonance causes a not exact zero current switching and the related phase voltage oscillation. However the current is purely sinusoidal without significant disturbs. A hybrid compensated structure is then tested starting from the parameters of the SS model. It is assumed that the current limit of the supply is about 5 $\mathrm{A_{rms}}$ so, the needed impedance of about 7 Ω, is obtained through an SP-S compensation topology. Referring to the diagram of Fig. 10, it is possible to evaluate the value of α that allows to obtain the searched impedance. Through the obtained value of α it is possible to determine the appropriate values of the series and parallel compensation capacitance using the diagram of Fig. 11. A list of the used values is proposed in Table II. Also in this case, looking at Fig. 12, it is possible to confirm the previous relationships. It is possible to note the presence of a 2 GHz oscillation over the fundamental wave form of the current. As explained in IV-A, this can represent

TABLE II: Parameters for SP-S compensation test

Parameter	Z_T	α	C_{1s}	C_{1p}
Value	$\approx 7\ \Omega$	≈ 0.2	33 nF	8.2 nF

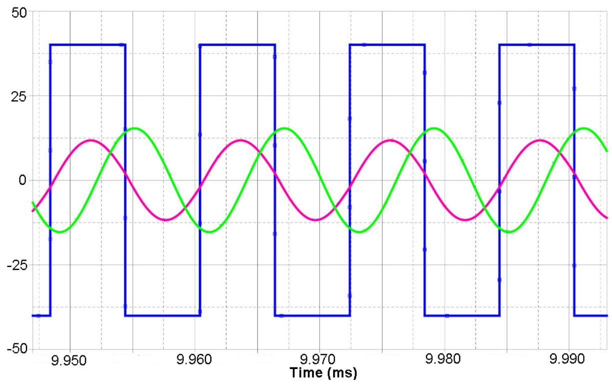

Fig. 8: Wave form of the PSpice simulated prototype. Source differential voltage (blue), primary current (magenta), secondary current (green)

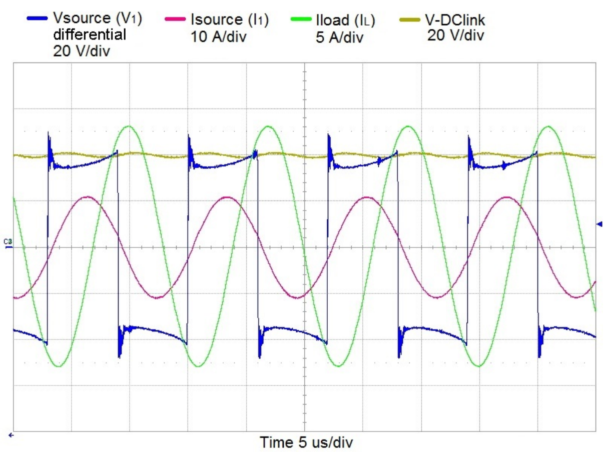

Fig. 9: Wave form of the prototype under test.

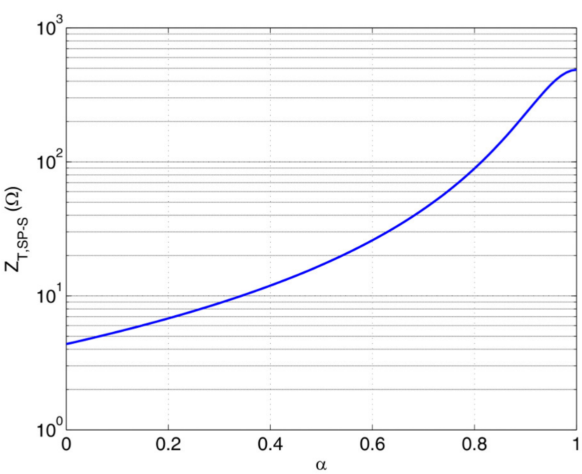

Fig. 10: Total impedance vs α for hybrid SP-S compensation

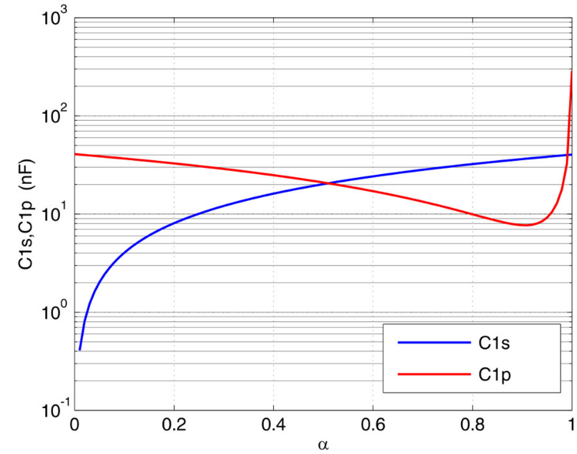

Fig. 11: Series and parallel capacitance vs α for hybrid SP-S compensation

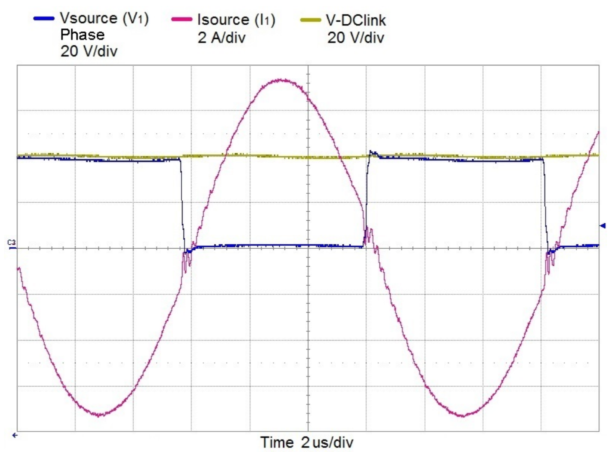

Fig. 12: Wave form of the prototype under test with SP-S compensation.

the principal problem in the power electronic control in an hybrid compensated system: it is important to reach the exact resonance.

VII. Conclusions

In this paper a novel and simpler structure for WPT for CWD is presented. The solution is based on a voltage supplied inverter. A new hybrid arrangement for the compensating capacitors for a CWD-WPT structure is proposed starting from an overview of the circuit theory of the mutual coupled inductors and the basic topologies for their capacitive compensation. The possibility to use these configuration in order to match the total impedance of the WPT structure is deeply investigated. A down-scale model under precise scaling rules was built and used for the theory verification. Different tests have been performed in order to examine the system behavior. They proved the feasibility of the proposed design solutions with an efficiency up to 80%. The motion of the receiving coil, the installation on the vehicle board and the real system realization will be the object of future works.

VIII. Acknowledgment

This work has been co-funded by the European Unions 7th Framework Program for Research, namely through the STREP eCo-FEV project (No. FP7 314411).

References

[1] M. Clothier, "Charging Mats Seen Boosting Market for Electric Vehicles" *http://www.bloomberg.com/news/2012-06-27/charging-mats-seen-boosting-market-for-electric-vehicles.html*, June 2012, Accessed in January 2014.

[2] M. Lamotta,"Toyota Licenses Wireless Charging Tech from WiTricity" *http://spectrum.ieee.org/energywise/green-tech/advanced-cars/toyota-licenses-wireless-charging-tech-from-witricity*, December 2013, Accessed in January 2014.

[3] *http://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/wcs.html*, Accessed in January 2014.

[4] M. Yilmaz, V. T. Buyukdegirmenci, P. T. Krein, "General design requirements and analysis of roadbed inductive power transfer system for dynamic electric vehicle charging," *Transportation Electrification Conference and Expo (ITEC)*, pp. 1–6, 2012.

[5] S. Lukic, Z. Pantic, P. T. v, "Cutting the Cord: Static and Dynamic Inductive Wireless Charging of Electric Vehicles," *IEEE Electrification Megazine*, vol. 1, no. 1, pp. 57–64, 2013.

[6] P. Ning, J.M. Miller, O.C. Onar, C.P. White, "A Compact Wireless Charging System for Electric Vehicles," *Energy Conversion Congress and Exposition (ECCE)*, pp. 3629–3634, 2013.

[7] M. Shwartz, "Wireless power could revolutionize highway transportation, Stanford researchers say", *Stanford Report on website http://news.stanford.edu/news/2012/february/wireless-vehicle-charge-020112.html*, February 2012, Accessed in January 2014.

[8] J. Huh, S.W. Lee, W.Y. Lee, G.H. Cho and C.T. Rim, "Narrow-Width Inductive Power Transfer System for Online Electrical Vehicles," *IEEE Transactions on Power Electronics*, vol. 26, no. 12, pp. 3666–3679, 2011.

[9] C.S. Wang, G.A. Covic, O.H. Stielau, "Design Considerations for a Contactless Electric Vehicle Battery Charger", *IEEE Transaction on Industrial Electronics*, vol. 51, no. 1, pp. 148–157, 2004.

[10] S. Choi, J. Huh, W. Y. Lee, S. W. Lee, Chun T. Rim, "New Cross-Segmented Power Supply Rails for Roadway-Powered Electric Vehicles," *IEEE Transaction on Power Electronics*, vol. 28, no. 12, pp. 5832–5841, 2013.

[11] J. Sallan, J.L. Villa, A. Llombart, J.F. Sanz, "Optimal Design of ICPT System Applied to Electric Vehicle Battery Charge," *IEEE Transactions on Industrial Electronics,*, vol. 56, no. 6, pp. 2140–2149, 2009.

[12] J. Shin, S. Shin, Y. Kim, S. Lee, B. Song, G. Jung, "Optimal current control of a wireless power transfer system for high power efficiency," *Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS), 2012*, pp. 1–4, 2012.

[13] M. Ryu, H. Cha, Y. Park, J. Back, "Analysis of the contactless power transfer system using modeling and analysis of the contactless transformer," *Industrial Electronics Society, 2005. IECON 2005.* 31^{st} *Annual Conference*, pp. 1036–1042, 2005.

[14] C.S. Wang, G.A. Covic, O.H. Stielau, "Power Transfer Capability and Bifurcation Phenomena of Loosely Coupled Inductive Power Transfer Systems", *IEEE Transaction on Industrial Electronics*, vol. 52, no. 5, pp. 1308–1314, 2005.

[15] D. Bavastro, A. Canova, V. Cirimele, F. Freschi, L. Giaccone, P. Guglielmi, M. Repetto, "Design of wireless power transmission for a charge while driving system", *IEEE Transactions on Magnetics*, vol. 50, no. 2, 2014.

[16] "SAE task force agrees on frequency of operation and power classes for wireless power transfer for light-duty plug-in vehicles", *Green Car Congress site http://www.greencarcongress.com/2013/11/20131115-sae.html*, November 2013, Accessed in January 2014.

[17] O.H. Stielau, G.A. Covic, "Design of loosely coupled inductive power transfer systems," *International Conference on Power System Technology, 2000. Proceedings. PowerCon 2000.*, vol. 1, pp. 85–90, 2000.

[18] N.A. Keeling, G.A. Covic, J.T. Boys, "A Unity-Power-Factor IPT Pickup for High-Power Applications," *IEEE Transaction on Industrial Electronics*, vol. 57, no. 2, pp. 744–751, 2010.

Vincenzo Cirimele received the M.Sc. degree in Electrical Engineering (summa cum laude) from the Politecnico di Torino, Turin, Italy, in 2013. From May 2013 to December 2013 he was research assistant and on January 2014 he became a Ph.D. student of the Department of Energy of the Politecnico di Torino. His current research interests are inductive power transmission and electromagnetic shielding of low frequency fields.

Fabio Freschi (SM '13) received the Laurea degree (summa cum laude) in Electrical Engineering at the Politecnico di Torino in 2002. On April 2006 he obtained the PhD degree and the European Doctorate Degree in Electrical Engineering. From January 2005 to July 2007 he was research assistant at the Electrical Engineering Department of the Politecnico di Torino. He is currently working as assistant professor in Fundamentals of Electrical Engineering at the Politecnico di Torino. His main research and scientific interests are related to numerical modelling and computation of electromagnetic and bioelectromagnetic fields. Part of his activity is related to the study and development of deterministic and stochastic optimisation algorithms applied to the study of electromagnetic devices and complex energy systems. He is author of more than 100 conference and journal papers in these fields. He is investigator of several of national and international research projects and he acts as referee of many international journals in the field of numerical electromagnetics, optimization and operational research.

Paolo Guglielmi (M '07) received the M.Sc. degree in Electronic Engineering and the Ph.D. degree in Electrical Engineering from the Politecnico di Torino, Turin, Italy, in 1996 and 2001, respectively. In 1997, he joined the Department of Electrical Engineering, Politecnico di Torino, where he became an Assistant Professor in 2002. Since 2012 he is Associate Professor at the Energy Department at the Politecnico di Torino. He is the author of several papers published in technical journals and conference proceedings. His fields of interest include power electronics, high-performance drives, and computer aided design of electrical machines.