Wireless Power Transfer with Data Transfer Capability for Electric and Hybrid Vehicles: State of the Art and Future Trends

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Keywords: Powerline Communications, Wireless Power Transfer, Electric and Hybrid Vehicles, Vehicle to Grid Data Exchange.

Abstract: This papers shows how Powerline Communication and Wireless Power Transfer technologies can be used together to allow both power and data transfer when hybrid and electric vehicles are connected to the grid. These two technologies have lately become popular when dealing with the Smart Grid environment (the former) and charging of electric powered devices (the latter). The authors have dedicated their research on the integration between them, keeping in mind their use in the automotive environment; this papers serves as a review and a starting point for future work in the area, offering a synthetic description of the operating principles and some results. In addition, shielding techniques for Wireless Power Transfer systems are shown and compared with each other, in order to show different aspects of this fundamental topic.

1 INTRODUCTION

Hybrid vehicles are nowadays being considered as a real alternative to internal combustion powered vehicles by a great percentage of people who are in the process of evaluating a new car. This big change in the last few year has been driven by ideological and political issues; in addition, most of the car makers have now hybrid vehicles in their production. Only considering economy of operation from the user point of view, the main turning point is the use of full electric vehicles or plug in vehicles, that obviously significantly reduces the fuel consumption.

Envisioning a constant increase of such vehicles, technologies that will allow easy data transfer from the vehicle to the grid (and vice versa) will become of common use; for instance, such data transmission could be in the area of infotainment, navigation information and statistics, diagnostics etc. Among the different technologies widely diffused allowing data transfer, Powerline Communication (PLC) has gained new life together with the birth of the so-called smart grid environment.

As for the battery charging, so far, to the authors' knowledge, all the commercially available electric or plug-in vehicles are equipped with a conductive charging equipment (either AC or DC), but a great quantity of studies and investments are directed towards the use of Wireless Power Transfer (WPT) technology, that will change the way we charge vehicles in the near future. This change is already ongoing as for consumer electronics products, since commercial products are already available (toothbrushes and mobile phone wireless chargers are of common use).

The present contribution works as a review paper, in which the basic concepts, applicatons and future trends are shown both for PLC and WPT, keeping in mind their use in the automotive environment. With this goal in mind, the authors have developed a hybrid PLC-WPT system, plus a new shielding technique suitable to reduce exposure to the electric field and the reuslts relative to these activities are shown here.

Section 2 is dedicated to the review of the Powerline communication technology and show how an implementation onboard an electric vehicle has been tested. Section 3 deals about the Wireless Power Transfer technology, and, in particular, describes a system that enables both power transfer and data transfer (with the PLC technology in mind). Section 4 shows the importance of shielding techniques, and also describes a new concept relative to the use of metamaterials in order to reduce exposure to the electric field.

Barmada, S., Fontana, N. and Tucci, M.
Wireless Power Transfer with Data Transfer Capability for Electric and Hybrid Vehicles: State of the Art and Future Trends.
DOI: 10.5220/0010484706620669
In *Proceedings of the 7th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2021)*, pages 662-669
ISBN: 978-989-758-513-5

2 PLC FOR VEHICLES AND SMART GRID APPLICATIONS

2.1 Technology Background

In recent years the use of Powerline Communication technology has gained renewed interest as a low cost way to allow integration of devices into a smart grid environment. With nowadays commercially available modems, data rates above 1Mb/s can be reached, making PLC an attractive technology that can compete with other communication technologies.

The recent development of the Home Plug Green PHY protocol (specifically dedicated to EVs) shows the future trend, and communication speeds of hundreds of Mbits per seconds can be reached (Kim et al., 2011; Son et al., 2010 and Joo et al., 2017).

In addition, when space and weight are a constraint, PLC technology can be fundamental to reduce cable harness onboard vehicles. Many studies are available showing how integration of PLC onboard different vehicles is a viable option and the signals that can be transmitted vary from usual control signals to Battery Management Systems signals. See for instance (Barmada et al., 2008, Lallbeeharry et al., 2018, Vincent et al., 2020, Sohn et al., 2019, Landinger et al., 2020, Krasovsky et al., 2020, IEEE Approved Draft Standard, 2018).

2.2 Measurements on a Specific Vehicle

In a previous work the authors (Amrani et al., 2013) have measured the performances of Vehicle to Grid (V2G) communication system between an electric vehicle and the power grid. In particular, the vehicle was plugged to the power grid during battery charging, and the communication channel was established between the cigarette lighter inside the vehicle and the same socked used for charging. These two access point were clearly not optimized, in order to be conservative in the measurements results. The system was also equipped with a low pass filter in order to filter-out the mains. For this specific vehicle, the ignition key can be in the “off” position; in “position I” (battery is connected to a limited set of auxiliary devices); in “position II” (all electrical devices energized and the inverter is turned on).

Figure 1 shows the transfer function of the measured channel with the ignition key in the positions mentioned before while Figure 2 shows the same measurement in the CENELEC narrowband. As known, considering usual noise scenarios, attenuations below 40db do not allow a reliable communication, however the figures show that above 300 kHz communication is possible, also considering that when V2G and G2V are considered, the vehicle can reasonably be turned off. The measurements for other in-vehicle channel can be seen in (Amrani et al., 2013) and are not reported here for the sake of conciseness.

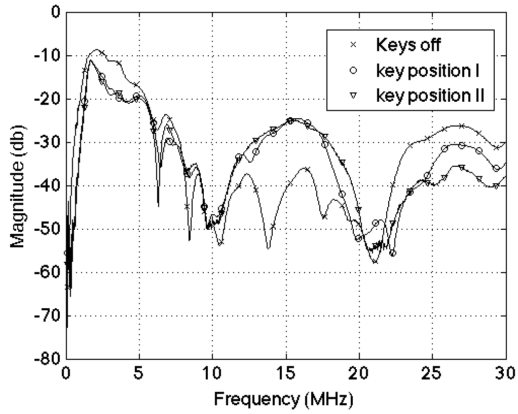

Figure 1: Transfer function of G2V channel.

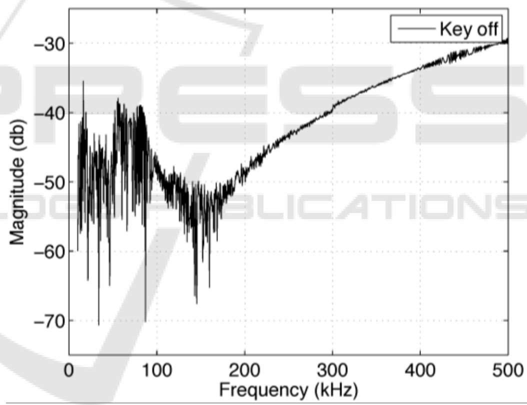

Figure 2: Transfer function relative to the CENELEC band limits.

2.3 Future Trends

As an overall comment, in most cases the communication signal has to “pass through” at least one converter (the AC/DC dedicated to battery charging) but often there is also the presence of a second one dedicated to the voltage reduction from the battery to the loads. From the communication point of view these are a bottleneck and in the future, in case V2G communication (not only for BMS) will become a standard requirement, specific circuitry could be designed with the aim of bypassing the inverters in specific frequency bands.

3 WPT WITH DATA TRANSFER CAPABILITY

3.1 Technology Background

Wireless Power Transfer (WPT) technology is nowadays a "hot" research topic that is witnessing investments both from public research centres and industry. Applications in the area of portable consumer electronic devices are already commercially available, while high power applications are in the course of prototyping. Charging of electric or hybrid vehicles is one of the most promising application of WPT technology, since the car manufacturers are strongly investing in the electrification of their production (Kurs et al., 2007, Lee et al., 2011, Madawala et al., 2011, Ahn et al., 2011, Hee Lee et al., 2020).

WPT for automotive applications can be implemented in different formats, from the most common two coils systems, to the multiple coil to achieve longer transmission distance; arrays of coils can be used when the position of the vehicle is affected by uncertainty, or when the vehicle charging should be considered as "dynamic", i.e. when the coils are places along a specific path the vehicle should follow.

In all these cases the trade-off between a cabled connection allowing a V2G communication (wireless communication is not always available, and needs additional equipment) and a wireless power charging is evident. This reason has led the authors in the recent past to propose a hybrid WPT – PLC system, that allows power and data transfer, having in mind the interaction with a power grid in which PLC technology (low cost) is used to implement communication in a smart grid environment.

3.2 Two Coils System

The two coils system is described in (Barmada et al., 2015) and it easily be represented by Figure 3. The two coils (that can be realized using different technologies) are the core of the system, and both power and data are transmitted through the inductive coupling. The bottom part of Figure 3 shows the usual power link (between ports 1 and 2), composed by the high frequency amplifier (on the Tx side) and the rectifier (on the Rx side), assuming that the system is used for battery charging. The capacitors C_a are responsible for the system's tuning at the desired frequency. The top part is responsible for the data transfer (between ports 3 and 4), with particular attention dedicated to a PLC link (working in frequency bands having tens of MHz in the upper limit).

The role of the high-pass filter and the capacitors C_b, C_c is the one usually performed by the capacitive coupler always present in PLC modems, that is to inject the high frequency signal into a low frequency power grid. In this particular system, these passive components also play the role as frequency decouplers between data and power, allowing the desired signal only to flow through the proper branch; in this way, correct and secure operations are guaranteed. The system could be of course designed to achieve bi-directional power and/or data transfer.

Figure 4 shows the channel capacity, evaluated with the Shannon Hartley equation, for a system prototype, described in (Barmada et al., 2017), characterized by two spiral coils (of square shape) whose longer dimension was 20cm. In particular, the channel capacity at different distances has been calculated, showing that (as it should be), shorter distances lead to better performances.

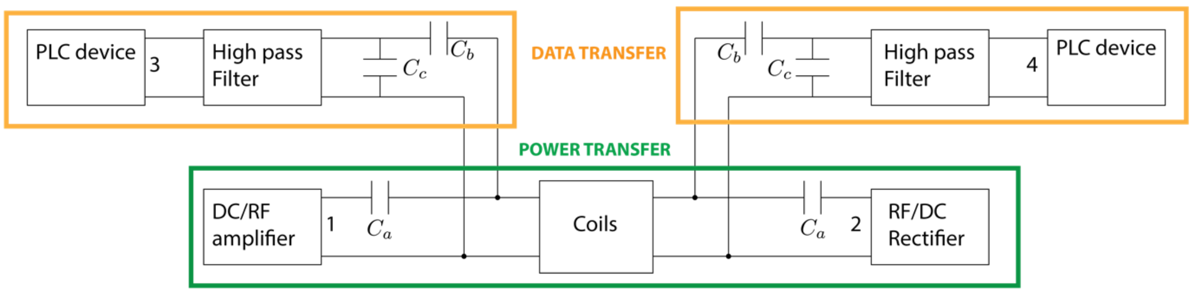

Figure 3: WPT – PLC system outline.

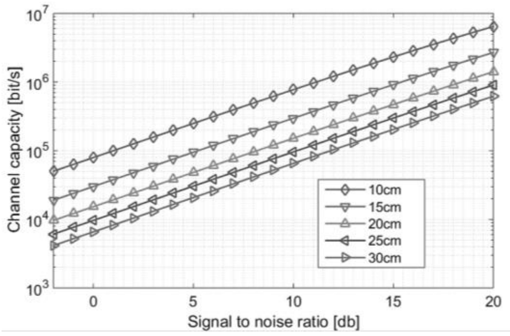

Figure 4: Channel capacity versus distance.

The Shannon Hartley equation allows the calculation of the ideal channel capacity as follows,

$$\begin{cases} C = B\, log_2\left(1 + \frac{S(f)}{I(f)+N(f)}\right) \\ S(f) = S_t(f)|H(f,d)|^2 \end{cases} \quad (1)$$

where $S(f)$ is the power spectral density of the received communication signal, $N(f)$ is the random noise spectral density at the receiver, and $I(f)$ is the narrowband interference power produced by the WPT circuit. B is the channel bandwidth, $S_t(f)$ is the transmitted signal's spectral density, and $H(f,d)$ is the communication channel's transfer function. In this case additive white Gaussian noise (AWGN) has been considered for the sake of simplicity. The use of eq. (1) allows a simple calculation of the theoretical channel capacity, and, despite its simplicity, is often use to calculate reasonable figures.

The graph shows that, at distances that are of the same order of magnitude than the coils, reasonable bandwidth for data communication can be achieved.

3.3 Multiple Coils Systems

The scheme shown in Figure 3 does not necessarily refer to the simple two coils systems, and the same concept can be applied to multiple coils systems (typically three or four) in which the additional loops (short circuited and physically placed between the transmitter and the receiver) play the role of repeaters. In these cases optimal performances can be achieved at the resonant frequency, at the cost having a bandwidth reduction; in addition, the additional coils contribute to the increase of joule losses, an issue that has to be taken into account as a trade-off between efficiency and power transmission distance.

Figure 5 shows the equivalent circuit of a four coils resonant system (valid for non radiative WPT), in which the coils connected to the source (V_S) and to the load (represented here by the resistance R_L) are (usually) called drive and load loops, while the short circuit repeaters are called Tx and Rx coils. Usual modelling of such system consists in a reasonable simplification, that is to consider only the coupling with the nearest neighbour (coupling coefficients k_{12}, k_{23}, and k_{34}).

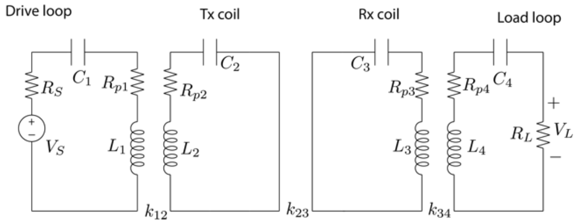

Figure 5: Lumped equivalent circuit of a four coils system.

Figure 6 shows a realization of the scheme shown in Figure 3, i.e. the data transmitter and receiver devices (i.e. V_T and R_R) are connected to the same ports with respect to the two coils through generic filters $\bar{Z}_P$ (whose role has been explained before).

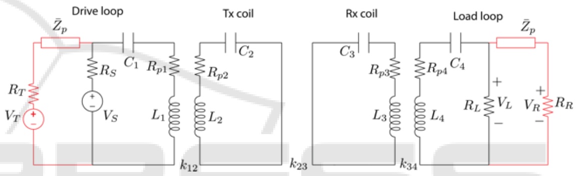

Figure 6: WPT – PLC system characterized by power and data having the same access point.

The possibility offered by having additional coils, is summarized in Figure 7 and proposed in (Barmada et al., 2019), in which an access point for data transfer has been created on the Tx and Rx coils, originally short circuited and simply used as repeaters. Here, the data source and data receiver (i.e. V_T and R_R) are coupled to the resonators by using parallel filters $\bar{Z}_S$ that have the role of short circuiting the power signal (that should not go through the transmission and receiver devices).

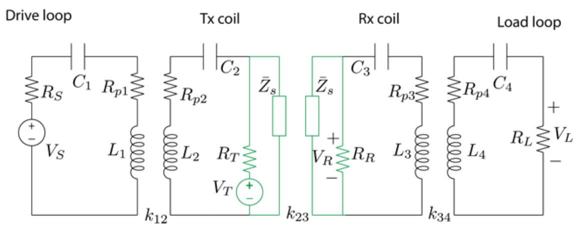

Figure 7: WPT – PLC system system characterized by power and data having different access points.

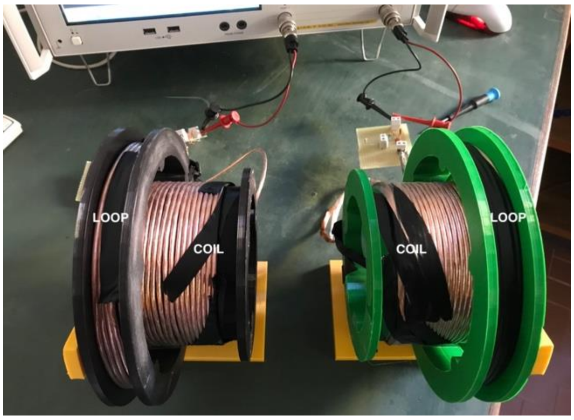

Figure 8: Prototype realization.

Figure 8 shows a prototype used to evaluate the convenience of creating the double access point as previously described. The details of the prototype (and the design criteria) are explained in in (Barmada et al., 2019); a set of measurements have been performed, at a distance $d = 5cm$ and $d = 15cm$ between the coils (case 1 and case 2), with different filter realizations (named “a” and “b”). The results shown here are relative to the longer distance and to a resonant frequency for the power transfer set to $f = 122.6\,kHz$, and are summarized in Figures 9, 10 and 11, in which “outer coils” refer to the system reported in Figure 6, while “inner coils” refer to the system shown in Figure 7.

Figure 9 shows the transfer function of the power channel, in which it is shown that, with a proper design of the filters, the presence of the data channel (and the relative equipment) does not alter the power efficiency.

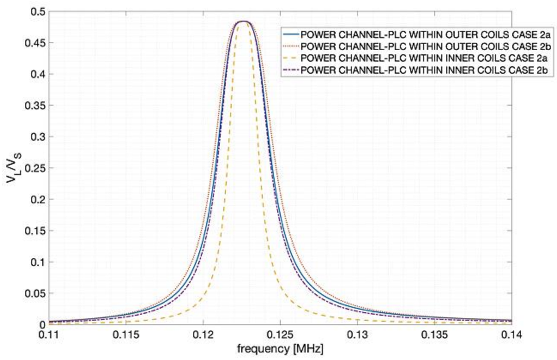

Figure 9: Power channel.

Figure 10 shows the transfer function of the data channel: in this case (data transfer) the curve’s most important characteristics to be taken into account is the bandwidth, and for the designed system, it can be understood from the figure that the data channel implemented with access on the repeaters (inner coils) has a better behavior than the data channel created on the power coils (outer coils).

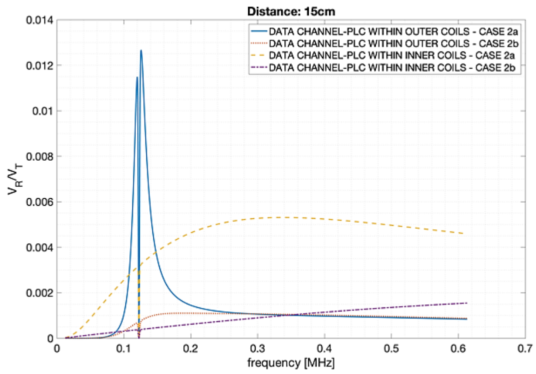

Figure 10: Data channel.

The qualitative analysis of Figure 10, is confirmed by the channel capacities (evaluated through the Shannon-Hartley equation) reported in figure 11.

The results shown here are relative to a specific system, with its own resonant system and its own set of filters. However, when a multiple coil system is adopted in order to achieve longer transmission distance, the theoretical and experimental results show that an additional data channel with better performances could be obtained.

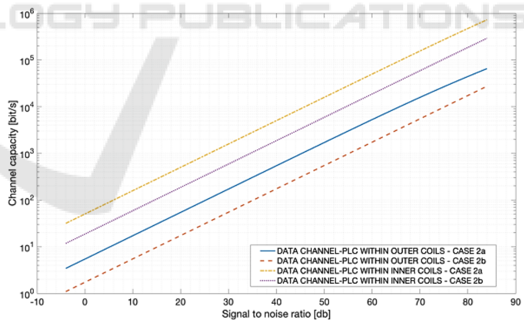

Figure 11: Data channel capacity.

3.4 Future Trends

As a final comment, the system proposed by the author shows that when using WPT systems to charge the battery of an electric or hybrid vehicle, it is also possible to create a data link without the addition extra elements. Such data link can be easily coupled with a pre-existing PLC system on a power grid, in order to achieve both power and data transfer.

The possibility of using additional ports for information exchange, made available by the presence of extra loops, can increase the communication performances between the vehicle and the grid.

The use of the data link should drive the design of the system's parameters; i.e. the transmission of infotainment data might require more bandwidth than diagnostics data etc.

4 SHIELDING ISSUES

When WPT systems are designed for high power uses, and when their use can take place close to human beings, shielding becomes an important issue. Several papers have been published on the topic, and some of them are specifically dedicated to vehicles (Cruciani et al., 2019 and Campi et al., 2020).

With the main goal to reduce cable harness, some authors are proposing WPT systems also to be used inside vehicles, in order to energize additional appliances that can be installed on the car (power seat or seat heater, for instance) or belonging to the passenger (Abul Masrur et al., 2019 and Seong-Ming et al., 2019).

These possible applications are of course prone to additional investigation related to shielding, since they "take place" inside the vehicle, where the driver/passenger and the WPT device are in close proximity.

In general, a lot of attention has been lately dedicated to the reduction of the magnetic field outside the coils; the most common approach is to use ferromagnetic slabs (properly designed in thickness and shape) that also contribute to the concentration of the magnetic field in between the coils.

Also active shields, implemented as coils driven by controlled sources, have been proposed in order to reduce exposure to WPT generated fields

The authors in (Brizi et al., 2020) focus their attention on the exposure to electric field (in a standard two coils system), that cannot be always neglected in close proximity to the coils. In particular, the authors propose a slab of metamaterial, that, based on experimental results and a physical interpretation, has the ability of reducing the electric field between the coils, retaining (actually, increasing), the power transfer efficiency).

The heuristic explanation behind effectiveness of the metamaterial slab in reducing the electric field, is the following: the electromagnetic field produced by a resonator is basically influenced by its dimensions (smaller coils are subject to smaller emf, hence smaller currents and consequent fields). Thus, with respect to the more common multiple coil systems, an array of smaller resonators (to a larger extent, a metamaterial) would lower the electric field measured at the surface of the transmitting side.

As a rule of thumb, there is a trade-off between the number of elements composing the array and the system performances. In particular, increasing the number of spirals decreases the electric field, but increases ohmic losses on the resonators themselves and lowers the resulting coupling between input and output (leading to an energy efficiency reduction).

The last two trends suggest that by employing a configuration with a high number of elements a further reduction of the electric field strength can be reached; however, the resulting mutual coupling and the efficiency of the system drops significantly.

Simulation on the system implemented by (Brizi et al., 2020), show that at a distance of 30cm (coil diameter is 18cm), the energy efficiency of a simple two coils system is lower than 10%. The inclusion of the matrix of resonators helps in increasing this value an reducing the electric field. In particular, with a 5x5 array, efficiency reaches the level of about 35% while the electric field is significantly reduced.

Metamaterials slabs with higher number of resonators lead to a further reduction of the electric field, but to a lower energy efficiency. On the contrary, lower number of resonators are characterized by higher efficiency but also higher electric field.

The selected metamaterial is an array of spiral resonators, realized with Litz wires wounded on plastic holders, and made resonant at the same resonant frequency as the WPT system. The experimental setup in (Brizi et al., 2020) showing a two coils WPT system with the 5x5 spiral arrays matrix is shown in Figure 12.

Figure 12: Wireless Power Transfer system with metamaterial slab.

The experimental results showed a relevant efficiency enhancement with the slab insertion and a reduction of the electric field in between the coils of more than 60% if compared to the regular system without slab.

As a final comment to this section, it is important to underline that shielding, both for increasing the power transmission and to reduce exposure to electromagnetic field is a fundamental issue and will be one of the most important design topic in the near future, when WPT systems will become commonly available.

Different frequencies are subject to different limits (see for instance the ICNIRP guidelines) and require different approaches and different shielding philosophies, ranging from ferromagnetic and conductive shields to active coils and metamaterials.

5 CONCLUSIONS

The present contribution shows how the powerline communication and wireless power transfer technology can work together to achieve both data and power transfer, with little modification to be done on either systems (if considered as stand-alone). Application to electric and hybrid vehicles is straightforward, and will see in the near future strong investments and research activity.

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