Theoretical Study of Different Access Points in coupled Wireless Power Transfer – Powerline Communication Systems

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Abstract ─ In this contribution the authors investigate the possibility of improving the performances of a coupled Wireless Power Transfer (WPT) - Power Line Communications (PLC) system in case the WPT system is characterised by a four coils structure. The main idea is to use the so-called transmitting and receiving coil (the two "inner" coils) as access point for the PLC modems and use the drive and load loops (the two "outer" coils) as usual access point for power transfer. The simulations results show that a wider band for communication is achieved with respect the previously proposed system.

Index Terms ─ Communication channel characterization, four-coils WPT, powerline communications, wireless power transfer.

I. INTRODUCTION

Wireless Power Transfer (WPT) technology has lately gained increasing attention as an alternative way to transmit power with respect to a cabled connection, see for instance [1] – [3].

In the last decade, Power Line Communication (PLC) has been recognised as a viable option for broadband communications. PLC technology uses power cables (where power is typically delivered at 50/60 Hz) to transmit high speed data. PLC communication is now considered one of the main possibilities to transmit data in a smart grid environment (when, for instance, long distances do not allow wireless data transmission).

As an example, [4]-[6] shows how PLC can be used in the smart grid environment with special attention dedicated to home appliances and plug-in electric vehicles.

These two technologies are apparently colliding, since WPT transfers power wirelessly while PLC transmits data on a cabled connection originally designed for power.

This has led the authors to the idea that a full integration between WPT and PLC could be a solution allowing the use of WPT without the need of changes to the pre-existing PLC system. In [7] a feasibility study of such system is proposed, in which a preliminary logic outline of the whole system is shown, and the evaluation of the available channel capacity is performed based on a typical four-coils system.

In [8] an optimization procedure performed on the lumped equivalent circuit is presented, showing that such system can be properly designed taking into account both power and data transmission requirements. In addition, in [9] the full system (with coils and filters) was designed and built showing the actual feasibility of the proposal. In particular, [9] is specifically referring to a two-coils WPT system, while in this contribution the authors investigate the possibility of using the inner coils of a four-coils system as access points for data transmission retaining the usual access point for the power (i.e., the "outer coils").

II. EVALUATION OF THE THEORETICAL CHANNEL CAPACITY FOR FOUR COILS-SYSTEMS

Figure 1 shows the typical four-coils WPT system, consisting of the drive and load loops (where the source and the load are connected) and the transmitting and receiving coils. The outer loops are used in order to achieve maximum power transfer when the transmission distance increases, reducing the coupling coefficient k_{23} between the inner coils. The inner coils have normally no access point and are often mounted on the same equipment as the relative loop. Still, in Fig. 1, we consider that the PLC transmitter (V_T , R_T) and the PLC receiver (R_R), are connected in series to the inner coils.

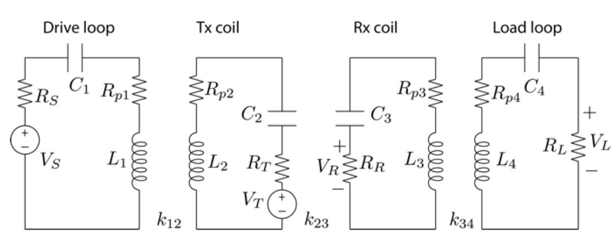

Fig. 1. Four-coils equivalent circuit.

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Equations (1) and (2) show the transfer function between the power source (V_S) and the power load (R_L), with $R_R = R_T = V_T = 0$, (in the following we introduce filters to obtain this condition at the resonance frequency), i.e., the system is in its standard WPT state:

$$\frac{\dot{V}_L}{\dot{V}_S} = R_L \frac{j\omega^3 k_{12} k_{23} k_{34} L_2 L_3 \sqrt{L_1 L_4}}{A\omega^4 + B\omega^2 + C}, \tag{1}$$

where

$$\begin{aligned} A &= k_{12}^2 k_{34}^2 L_1 L_2 L_3 L_4 \\ B &= k_{12}^2 L_1 L_2 \bar{Z}_3 \bar{Z}_4 + k_{23}^2 L_2 L_3 \bar{Z}_1 \bar{Z}_4 \\ &\quad + k_{34}^2 L_3 L_4 \bar{Z}_1 \bar{Z}_2 \\ C &= \bar{Z}_1 \bar{Z}_2 \bar{Z}_3 \bar{Z}_4 \\ \bar{Z}_1 &= R_{p1} + R_S + j\omega L_1 - \frac{j}{\omega C_1} \\ \bar{Z}_2 &= R_{p2} + j\omega L_2 - \frac{j}{\omega C_2} \\ \bar{Z}_3 &= R_{p3} + j\omega L_3 - \frac{j}{\omega C_3} \\ \bar{Z}_4 &= R_{p4} + R_L + j\omega L_4 - \frac{j}{\omega C_4}. \end{aligned} \tag{2}$$

Equations (3) and (4) show the transfer function between the data receiver R_R and the data source V_T, in which the load and source resistances R_S and R_L are not excluded, since data and power transmission take place at the same time:

$$\frac{\dot{V}_R}{\dot{V}_T} = R_R \frac{j\omega k_{23} \bar{Z}_1 \bar{Z}_4 \sqrt{L_2 L_3}}{A\omega^4 + B\omega^2 + C}, \tag{3}$$

where

$$\begin{aligned} A &= k_{12}^2 k_{34}^2 L_1 L_2 L_3 L_4 \\ B &= k_{12}^2 L_1 L_2 \bar{Z}_{3b} \bar{Z}_4 + k_{23}^2 L_2 L_3 \bar{Z}_1 \bar{Z}_4 \\ &\quad + k_{34}^2 L_3 L_4 \bar{Z}_1 \bar{Z}_{2b} \\ C &= \bar{Z}_1 \bar{Z}_{2b} \bar{Z}_{3b} \bar{Z}_4 \\ \bar{Z}_1 &= R_{p1} + R_S + j\omega L_1 - \frac{j}{\omega C_1} \\ \bar{Z}_{2b} &= R_{p2} + R_T + j\omega L_2 - \frac{j}{\omega C_2} \\ \bar{Z}_{3b} &= R_{p3} + R_R + j\omega L_3 - \frac{j}{\omega C_3} \\ \bar{Z}_4 &= R_{p4} + R_L + j\omega L_4 - \frac{j}{\omega C_4}. \end{aligned} \tag{4}$$

The reason why R_R and R_T are, on the contrary, excluded from the circuit in the previous evaluation comes from the fact that a filter to be placed on the coil is needed, with the aim of excluding the power dissipation on the PLC transceivers at the resonant frequency of the power transfer.

The above equations have been evaluated for a circuit model whose parameters are reported in Table 1, that are taken from [10]. The evaluation of the transfer functions as a function of the coefficient k_{23} allows the comparison between the two possible configurations in terms of channel capacity.

Table 1: Circuit parameters

Element	**Unit**	**Value**
$R_S = R_L = R_R = R_T$	Ω	50
$L_1 = L_4$	μH	1.0
$L_2 = L_3$	μH	20.0
$C_1 = C_4$	pF	235.0
$C_2 = C_3$	pF	12.6
$R_{p1} = R_{p4}$	Ω	0.25
$R_{p2} = R_{p3}$	Ω	1.0
$k_{12} = k_{34}$		0.1
k_{23}		$10^{-4} < k_{23} < 0.8$
f_0	MHz	10

III. SIMULATION RESULTS FOR THE SYSTEM WITHOUT FILTERS

Figure 2 shows the transfer functions (TF) between the outer coils according to equations (1) and (2), that is the regular WPT operating situation. The frequency splitting phenomenon and the maximum value close to 1 of the TF appear as expected.

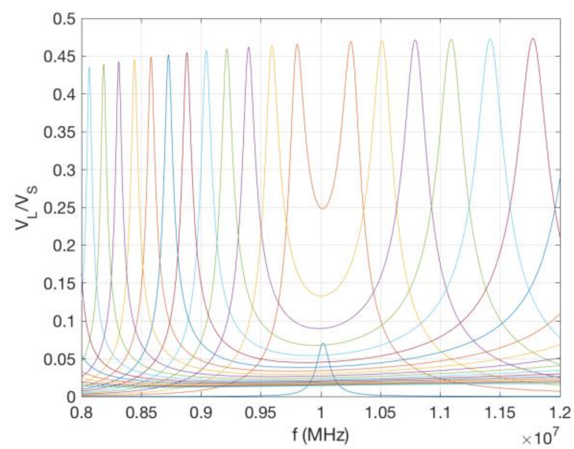


Fig. 2. Transfer functions between outer coils.

Figure 3 shows the transfer functions between the inner coils according to equations (3) and (4), i.e., when we suppose that data transfer happens between the inner coils. It is worth noticing that the maximum value of the TF is lower in this case, and this is consistent with the presence of the four resistances R_S, R_L, R_R, R_T; at the same time it is qualitatively evident that each single curve show a higher bandwidth if compared Fig. 2.

In order to better compare the performances of the two systems both the maximum value of each transfer function and the channel capacity (evaluated with a signal to noise ratio equal to 1) as a function of the coupling coefficient have been calculated.

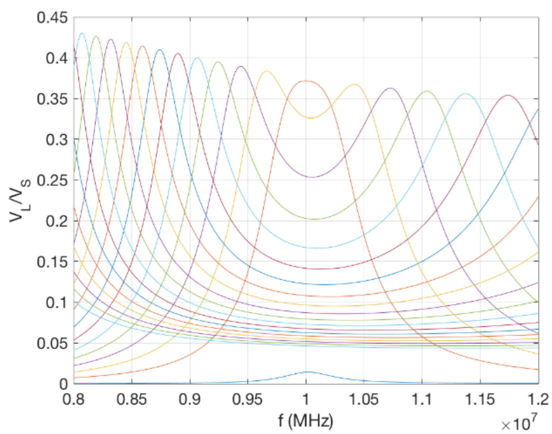


Fig. 3. Transfer functions between inner coils.

Figure 4 shows the maximum value of the TF (for inner and outer access point) as a function of the coupling coefficient: the maximum value is always higher in the first case, confirming that this is the best topology for power transfer (that should take place at the resonant frequency). On the contrary, Fig. 5 shows the channel capacity comparison: by looking at the figure it can be verified that for certain values of the coupling coefficient the achieved channel capacity (obviously proportional to the TF bandwidth) is higher: access from the inner coils guarantees better performances for a wide range of k_{23} values.

The results shown so far are relative to a basic system which does not take into account the need of filters which basically operate a separation between the power signal (characterized by a specific and designed frequency) and the data signal working on a (possibly) wide band.

In the following section the effect of the inclusion of basic filters has been added.

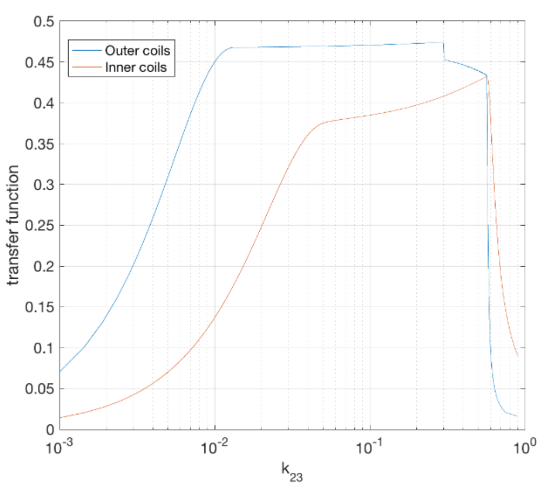


Fig. 4. Comparison between the maximum value of the transfer function.

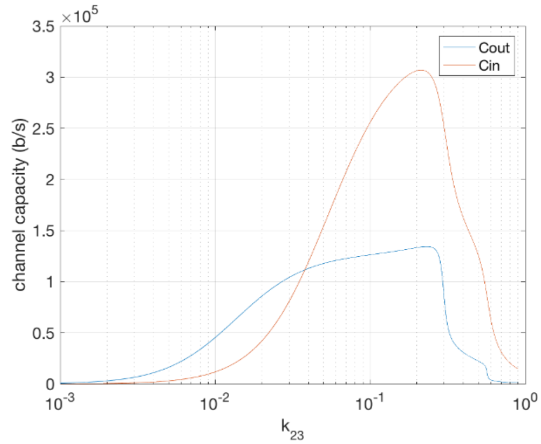


Fig. 5. Comparison between the channel capacity (S/N = 1).

IV. INCLUSION OF SECOND ORDER RESONANT FILTERS

The presence of additional filters is needed in the proposed combined system: they should prevent power to flow through the PLC modem (to avoid damages) and guarantee optimal coupling between the modem and the WPT system, possibly not affecting the power channel in terms of efficiency.

In this paper the authors have considered, for the sake of simplicity, second order parallel or series LC resonant circuits resonating at the power frequency f_0. Despite the simplicity of this approach, the results obtained clearly indicate that good performances can be achieved.

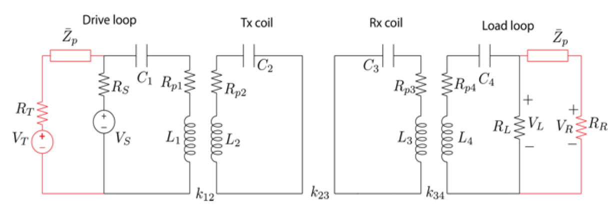


Fig. 6. Power and data from the outer coils, with the inclusion of the parallel filter.

The system in Fig. 6 is basically the one described in [7], with the parallel resonant circuit $\bar{Z}_p$ that resonates at the power frequency, hence operating as an open circuit. In this way the power signal (generated by $\dot{V}_S$ and received by R_L) does not flow into the PLC modem $\dot{V}_T$. On the contrary the wideband data signal generated by $\dot{V}_T$ and received by R_R is not affected by the higher magnitude power signal.

In Fig. 7 it is shown the new architecture proposed in this paper with the addition of the $\bar{Z}_s$ series resonant circuit (at the designed frequency). This series LC filter behaves as a short circuit at the power frequency, basically eliminating from the inner loops the modem and the transmitting and receiving loads (respectively $\dot{V}_T, R_R, R_T$): in this way power does not flow through the PLC modem and it is not dissipated into the receiving and transmitting resistances.

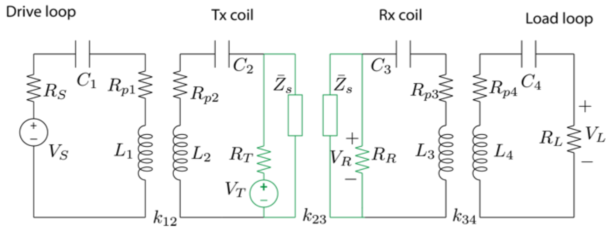


Fig. 7. Data from the inner coils, with the inclusion of the series filter.

At frequencies different from f_0, data signal can flow between the inner coils.

The TF of the two configurations have been analytically calculated with basic circuit theory, leading to expressions similar to equations (1) – (4) that are not reported here for the sake of simplicity. These expressions have been evaluated and the comparison between channel capacity was again calculated as before with a signal to noise ratio equal to 1.

V. SIMULATION RESULTS

Figures 8 and 9 show the TF of the circuit reported in Fig. 7, i.e., in the case data is transferred between inner coils and the corresponding LC series filers are added.

Analyzing Fig. 8 (relative to the power transfer), we can verify that far from the selected resonant frequency a performance decay (in terms of maximum value of TF, hence of transfer efficiency) is obtained. However, the resonant frequency of the system, which is the frequency at which power is transmitted, is chosen in the design phase and no drifting from this frequency should be allowed. For this reason, the results of Fig. 8 are acceptable from the WPT point of view.

Figure 9 shows the TF between the data points: because of the shunt filters, no data is received around the resonant frequency, but the TF is not negligible above and below f_0, resulting in the possibility of transferring data.

Figure 10 shows a comparison between the channel capacities calculated for the systems represented in Figs. 6 and 7. It can be easily seen that the configuration in which power and data are sent through different access points outperforms the one in which data and power share the same access point. At the same time, the use of the shunt filters in the inner coils to protect the PLC modem allows efficient power transfer if the working frequency is well defined and the filters are properly designed.

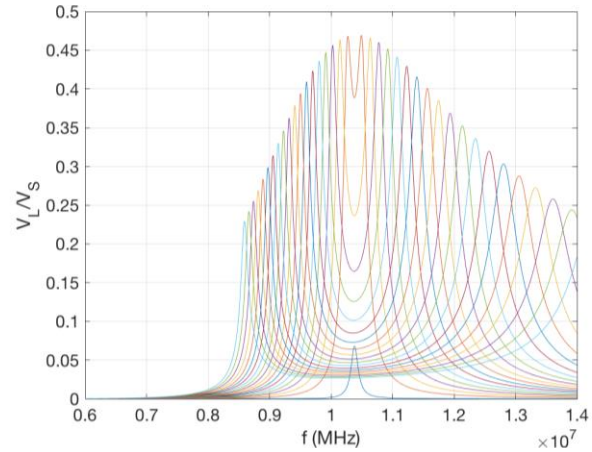


Fig. 8. TF between power terminals for the circuit with inner coils data access.

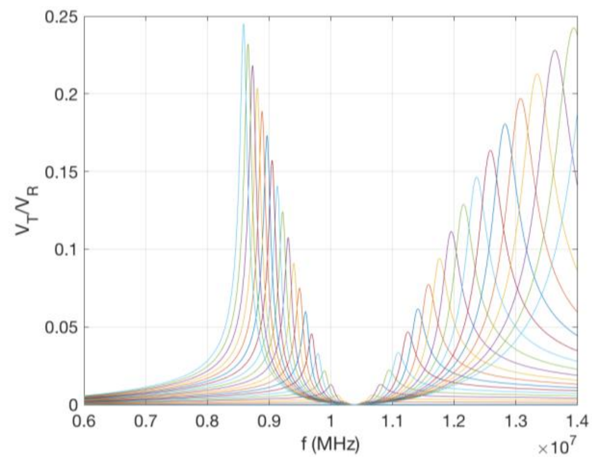


Fig. 9. TF between data terminals for the circuit with inner coils data access.

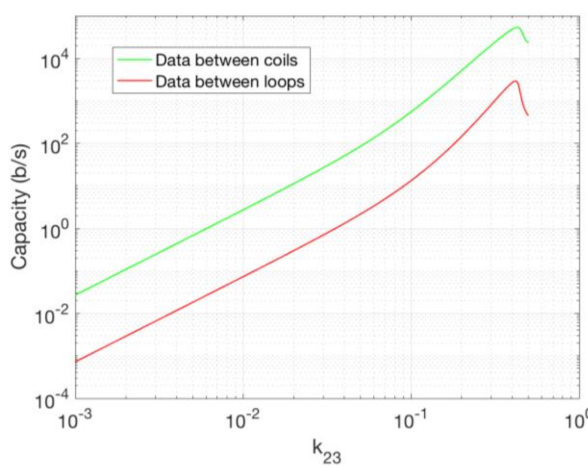


Fig. 10. Channel capacity comparison between different data access points in presence of filters.

VI. CONCLUSION

This preliminary study shows that in the case a four-coil WPT system is used (usually to increase transmission distance with respect to a two-coil system), the two inner coils could be used as access point to PLC data transfer. The numerical example shown here demonstrates that differentiating the access point (of power and data) leads to the achievement of a 30db higher channel capacity with respect to the case of using the outer access points (for a fixed value of k_{23}). As a general conclusion, the possibility of using different access points leads to new criteria in the design of WPT systems with data transmission capabilities.

The systems analyzed for comparison are characterized by second order L-C circuits, and the results of this study will be the object of future investigation and experimental validation.

REFERENCES

[1] A. Kurs, A. Karalis, R. Moffatt, J. Joannopoulos, P. Fisher, and M. Soljacic, “Wireless power transfer via strongly coupled magnetic resonances,” *Science*, vol. 317, no. 5834, pp. 83-86, July 2007.

[2] S. H. Lee and R. D. Lorenz, “Development and validation of model for 95%-efficiency 220-W wireless power transfer over a 30-cm air gap,” *IEEE Trans. Ind. Appl.*, vol. 47 no. 6, pp. 2495-2504, Nov.-Dec. 2011.

[3] U. K. Madawala and D. J. Thrimawithana, “A bidirectional inductive power interface for electric vehicles in V2G systems,” *IEEE Trans. Ind. Electron*., vol. 56, no. 10, pp. 4789-4796, Oct. 2011.

[4] S. Barmada, M. Tucci, M. Raugi, Y. Maryanka, and O. Amrani, “PLC systems for electric vehicles and smart grid applications,” *Proceedings of IEEE International Symposium of Powerline Communications and its Applications (ISPLC)*, Johannesburg, South Africa, pp. 23-28, 2013.

[5] M. Lienard, M. Carrion, V. Degardin, and P. Degauque, “Modeling and analysis of in-vehicle power line communication channels,” *IEEE Trans. Veh. Technol*., vol. 57 no. 2, pp. 670-679. Mar. 2008.

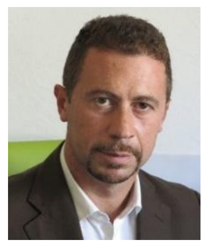
[6] M. Mohammadi, L. Lampe, M. Lok, S. Mirabbasi, M. Mirvakili, R. Rosales, and P. van Veen, “Measurement study and transmission for in-vehicle power line communication,” *Proceedings of IEEE International Symposium of Powerline Communications and its Applications (ISPLC)*, Dresden, Germany, pp. 73-78. 2009.

[7] S. Barmada, M. Raugi, and M. Tucci, “Power line communication integrated in a wireless power transfer system: A feasibility study,” *Proceedings of IEEE International Symposium of Powerline Communications and its Applications (ISPLC)*, Glasgow, UK, pp. 116-120, 2014.

[8] S. Barmada and M. Tucci, “Optimization of a magnetically coupled resonators system for power line communication integration,” *Proceedings of the IEEE Wireless Power Transfer Conference (WPTC)*, Boulder, CO, USA, pp. 1-4, 2015.

[9] S. Barmada, M. Dionigi, P. Mezzanotte, and M. Tucci, “Design and experimental characterization of a combined WPT - PLC system,” *Wireless Power Transfer*, Cambridge, vol. 4, no. 2, pp. 160-170, 2017.

[10] A. P. Sample, D. A. Meyer, and J. R. Smith, “Analysis, experimental results and range adaptation of magnetically coupled resonators for wireless power transfer,” *IEEE Transactions on Industrial Electronics*, vol. 58, no. 2, pp. 544-554 Feb. 2011.



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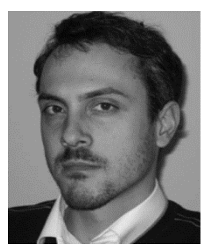

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