Simultaneous Wireless Power and Data Transfer: Overview and Application to Electric Vehicles

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Abstract— A Wireless Power Transfer System (WPTS) is basically constituted by two main parts: the primary side and the secondary side. Beyond the application related with the power transfer, also data communication between these two sides can be implemented and it can have a fundamental importance. In this paper, a classification that highlights the advantages and the disadvantages of different data communication techniques available in the literature is shown. The single link dual carrier (SLDC) technique is studied in depth, analysing transfer function of the power and data transmitting channels. A design example for electric vehicle wireless charging application in a Series-Series (SS) compensated system is presented. The analytical models are validated through simulations.

Keywords— Wireless Power and Data Transfer, Electric Vehicle.

I. INTRODUCTION

Inductive Wireless Power Transfer (WPT) is increasingly used in various applications. Its benefits are exploited to charge electric vehicles [1-2], aerial and submarines drones [3-4], biomedical implants [5] and sensors [6]. As well known, a WPT system can be divided into two main parts: the primary side and the secondary side. The primary side is usually made up from a DC-AC inverter used to impress a high-frequency AC voltage to the transmitter coil while the secondary side is constituted by the receiver coil and an AC-DC rectifier which is usually used to manage the received power regulating the current to charge the battery. In order to increase the transmission efficiency, the resonance between the coils inductances and some external capacitances is usually exploited.

As these systems divided into two parts, the communication between the primary and the secondary side is a complicated effort that plays a key role to achieve high system performance. Data transmission function can be used for several tasks such as load detection, battery status monitoring and output voltage feedback control. It can also be used for safety operation such as metal object detection to take a prompt decision and place the system in a safe condition.

Every communication takes place through a link, i.e. the physical channel that connect the primary to the secondary device. To perform the communication a carrier signal is used. This signal is usually sinusoidal, and it can be modulated varying its amplitude, frequency or phase-shifting depending on an input signal which represents the information that must be sent.

Depending on the number of link and carrier used, three main different techniques can be identified:

• Single Link – Single Carrier (SLSC): only one physical link is used for transmitting both the power and the communication data. To do that, the power signal is used as carrier and the amplitude is usually modulated depending on the communication signal, as shown in Fig.2(a). This technique has two main drawbacks; a) using the power signal as carrier, the data rate is limited to the power carrier frequency; b) for high power applications, the frequency is usually limited due to the physical limitation of the semiconductor power switches. Thus, this technique, does not allow to high-speed data rate.

• Dual Link – Dual Carrier (DLDC): The data and the power are transferred via an independent physical channel and the communication has its own carrier signal, as shown in Fig.2(b). Although this technique represents the simplest solution from the design point of view, this approach has two main drawbacks: a) multiple links will cause extra magnetic interfaces between two channels, the power signal acts as large noise for the data signal decreasing its signal to noise (SNR); b) higher infrastructure cost, complexity and size.

• Single Link – Dual Carrier (SLDC): this technique tries to exploit the advantages of the previous two approach. Because it does not use additional antenna (single link) but it is able to transmit data and power using different signals (dual carriers) achieving high-speed data transfer. By using this solution, the structure of the system and no extra coil is needed, as shown in Fig.2(c). Differently from the SLSC solution, the control of the power and data signal are independent from each other.

In this paper the most suitable for the electric vehicle wireless charging is studied in depth. The analytical results are validated through simulations.
In Fig. 1, a classification of the systems described in the literature is shown. The systems are classified in terms of power signal frequency $f_p$, data carrier frequency $f_d$, the power delivered to the load $P_o$, and type of techniques. Red dots refer to the SLDC [7-8], green points [9-10] refers to DLDC systems, and blue dots refers to SLSC systems [11-13]. The plot region is divided into three parts depending on the power delivered. The first region is the part with $P_o > 300$W. The second region is for $300 < P_o < 1$W. While the third part consists of the region with $P_o < 1$W.

A first consideration that emerges is that in those systems where the power that must be transferred wirelessly is rather high, the SLSC systems are preferred. This is because at higher powers the use of two separated link, like in the SLSC systems, becomes problematic due to interferences when the power of the wireless transmission system increases. When the $P_o$ is in the order of hundreds of mW, the DLDC is preferred since the interference problems are reduced. Moreover, working at a higher frequencies, the components and antennas dimensions are reduced, therefore the additional cost due to a higher number of devices is lower.

The SLDC systems, combining the advantages of both systems, represent the most flexible solution. This is confirmed by the user of these techniques in systems characterized by very different power ratings, as shown in [7] and [8].

For this reason, in the next sections, the SLDC is studied in-depth, and the electrical characteristics of the power and data channel using a series-series compensation topology are derived. A design example for a communication in an electric vehicle wireless charging system is proposed.
III. SYSTEM DESCRIPTION

The circuit topology of the proposed system is shown in Fig.3. As a new contribution with respect to that shown in [11], in this paper, a SS compensation topology is used.

![Circuit Topology Diagram]

**Fig. 3.** Circuit topologies. (a) Full circuit. (b) Power transmission circuit. (c) Data Transmission circuit.

The primary side is supplied by a high frequency full-bridge DC-AC inverter. In this paper the First Harmonic Analysis (FHA) is used to study the circuit, therefore the power supply is modelled by a sinusoidal voltage generator

\[ v_p(t) = \sqrt{2}V_p \sin(\omega_p t) \]  

(1)

Where \( \omega_p = 2 \pi f_p \). The power is transferred through two coils with inductance \( L_1 \) and \( L_2 \). The parasitic resistance of these coils due to skin and proximity effect are represented by \( R_1 \) and \( R_2 \). To increase the transmission efficiency and achieve the resonance, two external capacitances \( C_1 \) and \( C_2 \) are connected in series with the coils.

Concerning the data transmission, the case where the primary side is sending data to the secondary side is shown in Fig.3(a). Anyway, bidirectional communication can be easily performed adding a circuit able to operate both transmitter and receiver on both sides. To reduce the interference between the power and data transmission channels and increase the bit-rate, a data frequency \( f_p \) is applied to the communication cell.

The transmitting communication cell consists of two inductors magnetically coupled with a ferrite core. Differently from the inductance \( L_1 \) and \( L_2 \) which are coupled through the air. The data signal is added to the power signal through two inductors coupled by a ferrite core, thus their coupling coefficient is close to \( k=1 \). When the data are transmitted, a voltage \( v_d \) is applied to the communication cell. From the electrical point of view the coupling between the data communication coils is modelled through a primary leakage inductance \( L_{lp} \), a primary coil resistance \( R_p \), a secondary coil leakage inductance \( L_{ls} \), a secondary coil resistance \( R_s \) and a magnetizing inductance \( L_m \). The transmitting impedance seen from the resonant tank is \( Z_t \), while the receiving impedance is \( Z_r \). The circuit shown in Fig. 3(a) has two independent voltage source \( V_p \) and \( V_d \). To study the power and data transmission channel separately, the superposition principle is applied, leading to the power transmission circuit in Fig.3(b) and the data transmission efficiency in Fig. 3(c).

IV. POWER CIRCUIT ANALYSIS

The state space equation of the circuit in Fig.3(b) is

\[
\begin{align*}
[\dot{V}_t] &= 
[R + j(\omega - \frac{1}{\omega C}) + Z_t] - j\omega M [I_1] \\
[-j\omega M] &= 
[R + j(\omega - \frac{1}{\omega C}) + Z_t] [I_1]
\end{align*}
\]

(2)

To understand how to calibrate the primary and secondary capacitance \( C_1 \) and \( C_2 \) to increase the transmission efficiency, it is necessary to study the impedance \( Z_r \) and \( Z_t \). Defining \( n \) the turn ratio between the primary and the secondary coil, and defining \( \alpha = R_C(L_p + L_m) \) and \( \beta = R_P R_s C_2 + L_m L_p \), \( \gamma = R_s + R_p + \alpha \omega^2 \) the input impedance of the receiver cell \( Z_r = R_s + jX_r \) can be expressed as:

\[
R_s + \frac{-\omega^2 [L_s \beta + L_s (L_s + R_s R_p C_2)^{\ast}] + \beta [L_s + L_s (R_s + R_p + \alpha \omega^2 R_p R_s C_2)]}{\gamma^2 + \omega^2 \beta^2}
\]

(3)

\[
X_r = \frac{-\omega^2 [L_s \beta + L_s (L_s + R_s R_p C_2)^{\ast}] + \beta [L_s + L_s (R_s + R_p + \alpha \omega^2 R_p R_s C_2)]}{\gamma^2 + \omega^2 \beta^2}
\]

(4)

Denoting \( \varepsilon = (\alpha \omega C_2 (L_p + L_m) - 1) (\alpha C_2) \), the impedance of the transmitter circuit \( Z_t = R_s + jX_t \) can be written as:

\[
R_s = \frac{-\omega^2 [L_s \beta + L_s (L_s + R_s R_p C_2)^{\ast}] + \beta [L_s + L_s (R_s + R_p + \alpha \omega^2 R_p R_s C_2)]}{\gamma^2 + \omega^2 \beta^2}
\]

\[
X_t = \frac{-\omega^2 [L_s \beta + L_s (L_s + R_s R_p C_2)^{\ast}] + \beta [L_s + L_s (R_s + R_p + \alpha \omega^2 R_p R_s C_2)]}{\gamma^2 + \omega^2 \beta^2}
\]

(5)

(6)

Assuming to use the same highly-coupled inductor for both transmitting and receiving the data, when the receiver coils are highly coupled, the leakage inductance \( L_{lk} \) can be neglected leading to \( R_s = R_p \) and \( X_r = X_t = L_m \). Thus, at the power transmission frequency \( \omega_p \), the equivalent impedance seen from the power circuit is a series connection of the magnetizing inductance \( L_m \) and primary parasitic resistance \( R_p \). To maximize the transmission efficiency at the power transmission frequency, the external capacitances \( C_1 \) and \( C_2 \) are calibrated as follows:

\[
\omega_p = \frac{1}{\sqrt{L_m (L_m + L_s)}} = \frac{1}{\sqrt{C_1 (L_s + L_m)}}
\]

(4)

Under this condition the power transmission efficiency is:

\[
\eta = \frac{R_s}{R_s + R_p + R_s + \frac{R_s}{\omega^2 M^2} \left( \frac{\omega^2 C_2}{\omega} \right) + (R_s + R_p + R_s)^2}
\]

(5)

while the power delivered to the load \( R_L \) is:

\[
P_L = R_s \left( \frac{\omega^2 M^2}{R_s \left( R_s + R_p + R_s + \frac{R_s}{\omega^2 M^2} \right)} \right)
\]

(6)
Fig. 4. Bode plots. (a) Power channel. (b) Data transmission channel.

The transfer function of the power channel is:

\[ H_1(\omega) = \frac{V_1}{V_t} = \frac{Z_1 \cdot Z_2 \cdot Z_4}{Z_1 + Z_4 + (Z_1 + Z_4),} \]

(7)

where \( Z_1 = R_1 + j\omega L_1 + \frac{1}{j\omega C_1} \), \( Z_2 = R_2 + R_t + j\left(\omega L_2 - M + \frac{1}{j\omega C_2}\right) \), \( Z_3 = R_3 + R_t + j\left(\omega L_3 - M + \frac{1}{j\omega C_3}\right) \), and \( Z_4 = \frac{1}{j\omega C_4} \). The bode plot of the data communication channel can be calculated and it is shown in Fig.4(b). It is possible to see the bandwidth at the communication frequency.

V. DATA TRANSFER CIRCUIT ANALYSIS

The data transfer circuit is shown in Fig. 3(c). When a bit has to be transferred, a sinusoidal voltage \( v_t \) is applied:

\[ v_t(t) = \sqrt{2}V_0 \sin(\omega t). \]

The capacitances are calibrated as:

\[ \omega r_p = \frac{1}{\sqrt{C_1 (L_m + L_t)}} = \frac{1}{\sqrt{C_2 (L_m + L_t)}} \]

(9)

The transfer function of the power channel is:

\[ H_2(\omega) = \frac{V_r}{V_1} = \frac{Z_1 Z_2 Z_3}{Z_1 + Z_4 (Z_1 + Z_4).} \]

(10)

The voltage generated by the full-bridge inverter is modelled by a sinusoidal voltage generator. The power grid single-phase voltage has an RMS value of \( V_{grid} = 230 \text{V} \), thus the amplitude is \( V_{grid max} \approx 230 \text{V} \cdot 1.414 \approx 325.2 \text{V} \). This voltage is then rectified by an ideal full-wave rectifier, producing a constant voltage \( V_{DC} \approx V_{grid max} \). A high-frequency full-bridge inverter impresses a square wave voltage with 50% duty cycle between \( \pm V_{DC} \). Applying the first harmonic analysis (FHA), only the contribution of the first harmonic is taken into account. Thus, the sinusoidal voltage applied to the resonant tank has a frequency \( f_p = 85 \text{kHz} \) and an amplitude \( V_{1 max} = 4V_{DC} \pi \approx 415 \text{V} \). Its RMS value is \( V_r = V_{1 max}/1.414 \approx 293 \text{V} \).

In Fig.5(a) the bit sequence that must be transferred from the primary to the secondary side is shown. When a 1 has to be transferred, the high-frequency voltage \( v_t \) is applied to the transmitting circuit. On the other hand, when a 0 has to be transferred, the voltage generator \( v_t \) is disconnected. The blue trace represents the received voltage across the resistance \( R_r \). The enlargement shows that \( v_r \) is the sum of two sinusoidal voltages: the carrier at \( f_p = 85 \text{kHz} \), and the modulation at \( f_p = 2 \text{MHz} \). The amplitude of the voltage across \( R_r \) is \( V_{grid max} \approx 230 \text{V} \). A high-frequency full-bridge inverter impresses a square wave voltage with 50% duty cycle between \( \pm V_{DC} \). Applying the first harmonic analysis (FHA), only the contribution of the first harmonic is taken into account. Thus, the sinusoidal voltage applied to the resonant tank has a frequency \( f_p = 85 \text{kHz} \) and an amplitude \( V_{1 max} = 4V_{DC} \pi \approx 415 \text{V} \). Its RMS value is \( V_r = V_{1 max}/1.414 \approx 293 \text{V} \).

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VII. CONCLUSIONS

In this paper, after an overview of different techniques used to transfer the power and data simultaneously are studied, the application of the SLDB is applied to a WPT suitable for battery charging utilizing a series-series compensation. The advantages and disadvantages of each techniques are highlighted. The design and the simulation of a single link dual band (SLDB) system are given for an EV wireless charging system. An analysis of the power and data channel is carried out. Results of simulations confirm both the validity of the mathematical model and the good performance in terms of interference between the two channels.

![Simulation waveforms. (a) Transmitted Bit sequence and received voltage \( v_r \). (d) Transferred power \( P_r \).](Image)
REFERENCES


