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Resonant Inductive WPT link with Load–Independent Voltage Gain

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Abstract

This paper investigates the possibility of achieving a load–independent output voltage for a resonant inductive Wireless Power Transfer (WPT) link.

1 Introduction

Resonant inductive Wireless Power Transfer (WPT) is an attractive solution for contactless recharging of electronic devices and systems [1] –[2].

In this regard, among the possible operative regimes that have been discussed in the literature [3, 4], of particular interest is the one providing a load–independent output voltage [5]–[7].

Accordingly, referring to an inductive WPT link using series resonators, in this paper the feasibility of achieving an output voltage independent of the load value is discussed. It is shown that, when the load is greater than a threshold value which depends on the link parameters, a load–independent output voltage can be realized by an appropriate selection of the operating frequency.

2 Problem description

The WPT link analyzed in this paper consists of two magnetically coupled inductors with appropriate series compensating capacitors. A possible lumped element equivalent circuit is the one illustrated in Fig. 1, where $n = \sqrt{L_P/L_S}$. The capacitances C_1 and C_2 realize the resonance condition at the frequency $f_0 = \omega_0/(2\pi)$. The magnetic coupling coefficient $k = M/\sqrt{L_P L_S}$ is used to represent the magnetic coupling between the inductors L_P and L_S. It is assumed that a generator with internal resistance R_G is on port 1 and that a resistive load R_L is on port 2.

Depending on whether the generator on port 1 is a current or a voltage generator, by using the ABCD matrix to represent

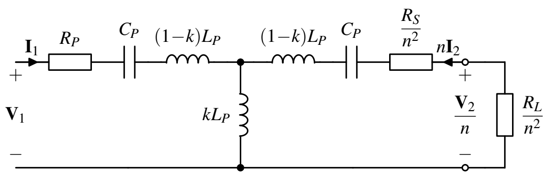

Figure 1. Equivalent circuit of the WPT link referred to primary.

Table 1. Normalized resistances

$r_P = R_P/X_P = 1/Q_P$	$r_S = R_S/(n^2 X_P) = 1/Q_S$
$r_G = R_G/X_P = 1/Q_G$	$r_L = R_L/(n^2 X_P) = 1/Q_L$
$r_{PT} = r_P + r_G = 1/Q_{PT}$	$r_{ST} = r_S + r_L = 1/Q_{ST}$

the two–port network, the following gain definitions can be introduced:

$$
\begin{aligned}
G_{VV} &= \frac{V_2}{V_1} = \frac{R_L}{AR_L + B} \\
G_{VI} &= \frac{V_2}{I_1} = \frac{R_L}{CR_L + D}
\end{aligned}
\tag{1}
$$

The goal of the present paper is to derive the general conditions for realizing a load–independent voltage gain (i.e., values of G_{VV} or G_{VI} independent of R_L). For a generic two–port network, from (1), it can be easily verified that:

- a load–independent voltage controlled voltage gain (VCVG) can be achieved for $B = 0$, which leads to $G_{VV} = 1/A$;
- a load–independent current controlled voltage gain (CCVG) can be achieved for $D = 0$ which leads to $G_{VI} = 1/C$.

In the following section, the conditions for realizing the two above reported schemes will be firstly derived for the case of a lossless WPT link (i.e., for the case where $R_P = R_S = 0$) and then their feasibility for a lossy link will be verified.

3 Conditions for a constant voltage gain for a resonant inductive WPT link

Referring to Fig. 1, the normalized resistances reported in Table 1 are introduced and adopted for the analysis. The reactance slope parameter of the primary resonator $X_P = \sqrt{L_P/C_P}$ has been used for normalization. For convenience, the normalized frequency $u = \omega/\omega_0$ is also introduced. For given parameters of the network, frequency dependent expressions can be derived for the terms of the ABCD matrix.

In particular, in the lossless case, it can be easily verified that:

- the term B nullifies at the frequencies: $u_{L,H} = \frac{1}{\sqrt{1 \pm k}}$;
- the term D nullifies at the resonant frequency: $u = 1$.

The same calculation can not be done in the lossy case because it would lead to complex frequencies; however, it is possible to derive the expressions of the output voltage at the frequencies $u_{L,H}$ and then to verify the feasibility of the load-independent VCVG and CCVG schemes.

In more detail, it can be easily verified that in the lossy case the expressions of the output voltage at the frequencies $u = u_{L,H}$ and $u = 1$ depend on R_L.

However, it is possible to demonstrate that it is possible to realize a VCVG scheme at $u_{L,H}$ and a CCVG scheme at $u = 1$ when the link satisfies the following condition:

$$\frac{n\,Q_i R_L}{X_p} = \frac{n\,r_L}{r_i} >> 1, \tag{2}$$

In fact, when (2) is satisfied, the output voltage at the frequencies $u_{L,H}$ and $u = 1$ is asymptotically independent of R_L.

In the following section circuital simulation results and experimental data validating the analytical formulas reported in this section will be reported and discussed

4 Results

In order to verify the theoretical formulas discussed in the previous section, the link described in Table 2 has been investigated. The equivalent circuit illustrated in Fig. 1 has been analyzed by using the circuital simulator NI AWR design environment; the considered case is the VCVG (Voltage Controlled Voltage Gain), realized at u_L and u_H.

The results obtained for the output voltage are reported in Figs. 2–3. In more detail, Fig. 2 shows the results achieved for the lossless case (i.e., for $R_P = R_S = 0$); circuital simulations confirm that a load–independent output voltage can be obtained at u_L and u_H. The results calculated for the lossy case are given in Fig. 3, as it can be seen, circuital simulations confirm the theoretical formulas. In fact, according to (2), the output voltage at u_L and u_H assumes approximately the same value when the load value is large enough as R_{L3}, R_{L4}, R_{L5}.

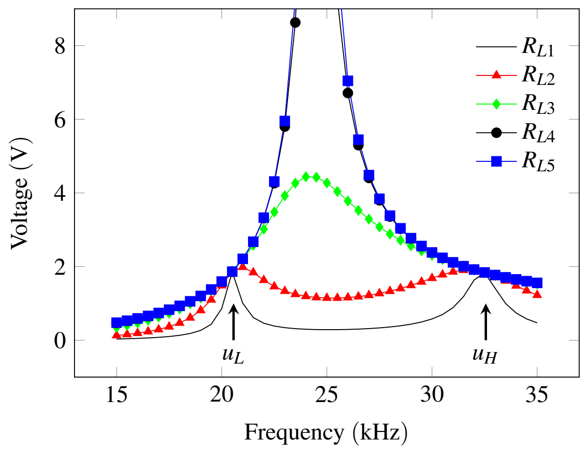

Figure 2. Circuital simulation results achieved for the voltage on the load for the lossless case. The considered load values are: $R_{L1} = 1.33\,\Omega, R_{L2} = 5.32\,\Omega, R_{L3} = 20.27\,\Omega, R_{L4} = 100\,\Omega, R_{L5} = 1993.7\,\Omega$

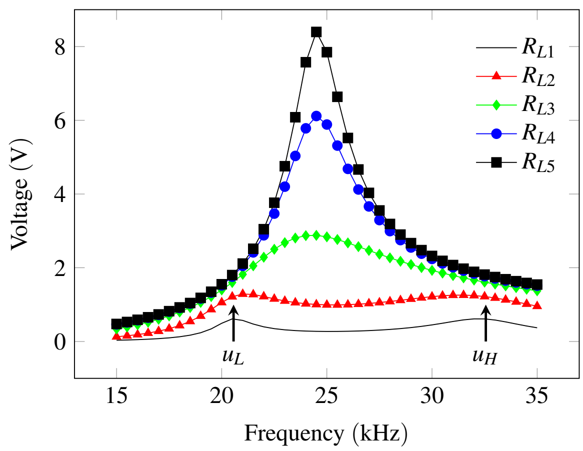

Figure 3. As in the previous figure but for the lossy case.

5 Conclusion

In this paper the feasibility of achieving a load–independent voltage gain for a resonant inductive wireless power transfer link has been discussed. It has been shown that for high quality resonators, a load–independent output can be realized by an appropriate selection of the operating frequency. Circuital simulation results validating the theory have been also reported.

References

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Table 2. Values of the coils.

f_0 (kHz)	L_1(μH)	L_2(μH)	C_1 (nF)	C_2 (nF)	R_P (Ω)	R_S (Ω)	Q_1	Q_2	n
24.48	128	128	330	330	0.83	0.83	23.73	23.73	1

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