Sensitivity Analysis of Component's Tolerance in Inductively Coupled Power Transfer System

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***Abstract*—ICPT systems help drivers to recharge their electrical vehicles via wireless. The core of the system is a pair of coils and two reactive structures. In order to predict the performance of a practical implementation, it is necessary to study the impact of using real components which suffer from variations in their nominal values. Basing on the performed study, we conclude that the components on the side where the inductance is in series with the capacitance should be carefully selected as variations in their values greatly affect the system performance. A 50 kW system has been evaluated in terms of efficiency and load voltage.**

Keywords-electric vehicle, inductively-coupled power transfer, tolerance, components

I. INTRODUCTION

Electric vehicles represent a less pollutant alternative to transport systems supported by internal-combustion engines. In addition to this environmental advantage, drivers appreciate the reduced costs of electricity in comparison with fuel. These two conditions have prompted that electric vehicles are acquiring a major relevance nowadays. However, their expansion is being refrained because of their scarce resource autonomy. This limitation demands frequent recharging processes, in which the driver needs to plug a conductor to the vehicle and to wait until the vehicle has been charged. In order to make this activity more efficient and with minimal users' intervention, ICPT (Inductively-coupled Power Transfer) systems are being developed.

The core of an ICPT is composed of two coupled coils operating at VLF (Very-Large Frequency). Both coils are complemented with reactive structures so that the battery gets the maximum real power from the source.

Depending on the components of the reactive structures, the compensation topologies can be classified into single-resonant and multi-resonant [1]. The single-resonant structures associate a capacitor to each coil whereas multi-resonant topologies employ multiple reactive components in the transmitter and/or the receiver coil. In addition to their simplicity, there exists a wider study on the single-resonant structures so that some design guidelines have already been identified. These recommendations help the design of an ICPT system. For instance, [2] recommends that the Q-factors of the primary (q_p) and secondary (q_s) sides should be between 5-10. Alternatively, [3] also suggests the use of a q_s in the range 5-10 and a $q_p > 2$.

Following the design guidelines, one can derive defined values for the coil parameters (L_1, L_2, R_1 and R_2) and for the compensation topologies (C_1 and C_2 in a single-resonant structure) at a given operational frequency. However, the physical components are associated with some tolerances in their nominal values. For instance, [4] shows a practical implementation of a 5 kW ICPT. Although the coil dimensions have been carefully decided, the practical inductance and resistivity values differ from the expected ones. Specifically, the resistances associated to the coils are doubled in the practical implementation. On the other hand, the real value of the inductance differs in up to a 20% of the nominal set.

Thus, the selection of the components must attend their potential deviations in order to obtain robust ICPT systems. Particularly, the more severe the consequences of the deviations are, the more precise the components should be in a practical implementation. The present paper identifies which elements in the ICPT system should have a lower tolerance. Towards this goal, the paper analyses how significant the effects of the components' tolerance are. The performance of an analytical model of a 50 kW ICPT system is studied for this purpose. Although the SP compensation topology is mainly studied in this paper, we include some results derived from the PS (Parallel-Series) structure to understand how the placement of the components affects the robustness of the ICPT system.

The rest of the paper is structured as follows. Section II describes some works dealing with the tuning of the ICPT system. Section III focuses on the SP compensation topology. Section IV illustrates and analyses the results obtained when the components' values are varied. Finally, Section V draws the main conclusions of the paper.

II. RELATED WORK

Some previous works have dealt with the deviations of two important parameters related to the operation of an ICPT system. These parameters are the coil misalignment and the operational frequency. The main conclusions about these works are presented next.

A. Coil Misalignment

An ICPT system is designed assuming that the coil in the electrical network and the coil in the vehicle keep a predefined distance (known as gap) and they are facing each other. Under these circumstances, the efficiency of the system is maximum whereas angular, lateral or incorporated misalignments lead to a reduced efficiency [5] for both circular [6] and rectangular. [7] structures. The reduction of the efficiency is due to the fact that an incorrect positioning of the receiver implies that a decremented magnetic flux traverses the pickup. As a consequence, the mutual inductance and, in turn, the induced voltage are also diminished.

In order to guarantee the designed efficiency, some ICPTs are equipped with sensor-based guidance systems so that the receiver is placed in the desired position while recharging [8] [9]. The main drawback of this strategy is the requirement for the user's intervention. As an alternative, some approaches opt for incorporating customized technology to mitigate the misalignment consequences. In this sense, complex pickup structures are designed in [10]. Basically, they implement quadrature pickups in order to benefit from horizontal and vertical magnetic flux. Nevertheless, this kind of solution forces the inclusion of more expensive equipment in the receiver. It is worth noting that it is desirable to reduce the costs in the receiver for vehicle chargers so this strategy is not usually implemented. On the other hand, some research works propose specific multi-resonant compensation topologies which are able to cope with coil misalignments [11]. As an advantage, these structures are placed in the transmitters.

B. Operational Frequency

The battery/load electrical features depend on several factors such as the State-of-Charge or the State-of-Health. Thus, the ICPT system must be able to work on different battery conditions. Towards this goal, the ICPT is supplemented by a control system that adapts some configuration parameter as the duty cycle or the frequency of the switched-mode power devices. Concerning this last tuning, it is necessary to analyze the capability of the ICPT system to work under different operational frequencies. In this sense, it is mandatory to design the ICPT to avoid the bifurcation phenomena [12]. When implemented by single-resonant compensation topologies, this requirement is equivalent to set the Q-factors according to some recommendations.

To the authors' knowledge, no previous study has addressed the consequences of having different values of the components being part of the ICPT system.

III. ANALYSIS OF THE SP COMPENSATION TOPOLOGY

Compared with other single-resonant structures, the SP (Series-Parallel) compensation topology offers some convenient advantages. [13] argues that the SP architecture is the best choice as a battery charger with a voltage source input given the current limitation imposed by the parallel compensation on the secondary side. Moreover, [14] concludes that series compensation on the primary side is more effective to eliminate the effects of the leakage inductance.

The SP compensation topology is characterized by two capacitors, each one connected to a coil. Particularly, capacitor C_1 is connected in series to the primary coil whereas capacitor C_2 is in parallel with the secondary coil. Figure 1 illustrates this connection.

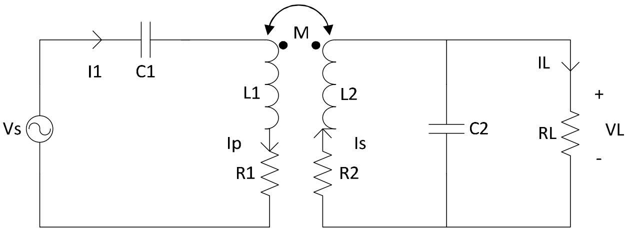

Figure 1. Illustration of the core of an ICPT system with an SP compensation topology.

The sinusoidal source is derived from an H-bridge inverter which converts the electrical input voltage (50-60 Hz) to a higher frequency (20 kHz in our study). Our analysis focuses on a 50 kW design. In this particular case, the fundamental harmonic of the 400 V electrical supply has an amplitude equal to 510 V. On the other hand, the operational frequency belongs to the VLF range in order to make the wireless transfer more efficient. We have opted for a 20 kHz switching frequency in the inverter.

The values associated to the coils (L_1, L_2, R_1, R_2 and M) depend on the structure of the coils, on their geometry and on the material with which they are constructed. In our design, we are considering rectangular coils constructed with Litz cable. With this type of cable, the resistance is less dependent on the frequency than cupper. The inductances are designed to guarantee that the system could not operate under bifurcation phenomena in frequencies different to the operational one.

Once decided, the designer must select the convenient C_1 and C_2. To deliver the maximum power to the load, the secondary side constitutes a resonant tank. Thus:

$$\omega_o = \frac{1}{\sqrt{L_2 C_2}} \tag{1}$$

where ω_o is the angular operational frequency, that is, $40\pi \cdot 10^3$ rad/s.

On the other hand, C_1's value is selected to compensate the imaginary part on the primary side as expressed in Eq. 2. This relationship strongly depends on the compensation topology.

$$\left(L_1 \frac{1}{\sqrt{L_2 C_2}} - \frac{\sqrt{L_2 C_2}}{C_1} \right) = \frac{M^2}{\sqrt{L_2 C_2} L_2} \tag{2}$$

Operating on the previous equations, the capacitances of C_1 and C_2 are determined as follows:

$$C_2 = \frac{1}{\omega_o^2 L_2};\ C_1 = \frac{L_2^2 C_2}{L_1 L_2 - M^2} \tag{3}$$

The values for the capacitances depend on the compensation topology. For other single-resonant topologies, please refer to [12].The studied system provides 500 V to an Ion-Lithium battery. The values of the ICPT components are summarized in Table I.

TABLE I. ICPT PARAMETERS

Component	Value in the SP topology	Value in the PS topology
L_1	260,39 μH	6.62 μH
L_2	7,59 μH	256,98 μH
M	7,67 μH	6,67 μH
Coil geometry	Planar	Planar
L_1 dimensions	04 x 0.8 m^2	04 x 0.8 m^2
L_2 dimensions	0.4x0.4 m^2	0.4x0.4 m^2
R_1	0.013 Ω	526.3 $\mu\Omega$
R_2	280.7 $\mu\Omega$	0.012 Ω
Q_p	6.41	5.88
Q_s	5.23	6.45
C_1	250,63 nF	9.28 μF
C_2	8,33 μF	246.4 nF
Load voltage (V_{LO})	*500 V*	*500 V*
Nominal efficiency ($efficiency_0$)	*99.3%*	*99.3 %*
Gap	*15 cm*	*15 cm*

We have included the design values for the PS topology in Table I. This structure could be considered as the opposite to the recommended one. It is worth analyzing how the position of the capacitances affects to the robustness of the system.

IV. IMPACT OF THE COMPONENTS' TOLERANCE

Considering a single-resonant compensation topology, the components which are prone to variations are: capacitors C_1 and C_2 (their capacitances), coil L_1 and L_2 (self-inductances, resistances and mutual inductance).

Next we present the variations of the system performance when the components suffer from deviations in their values. Firstly, the system performance is modeled considering SP and PS compensation topologies. Then, the model is coded in MATLAB [15]. In this developed code, we force the variations of the main components of the ICPT system once it has been designed as summarized in Table I. Due to space limitations, we present the results related to the system efficiency and the load/battery voltage (V_L). The results are referred to their expected behavior (*efficiency*$_o$ and V_{L0}) when the components are associated to the exact designed values.

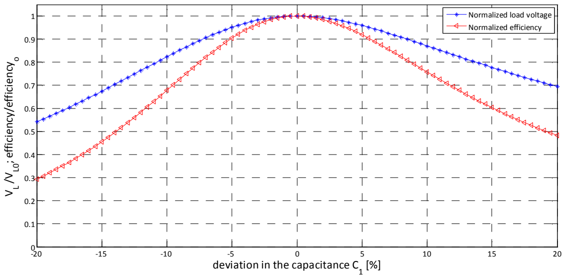

Figure 2. Variation of C_1's capacitance for the SP compensation topology.

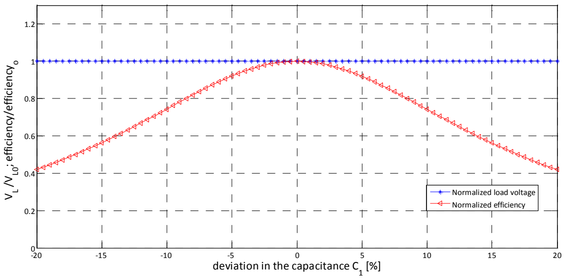

Figure 3. Variation of C_1's capacitance for the PS compensation topology.

Analyzing Figures 2 and 3, we observe that the variations of the C_1's capacitance strongly impact on the efficiency and the load voltage when it is in Series with the primary coil. Specifically, when the C_1's capacitance is decreased to a 10% of its nominal value, the efficiency of the system is sharply reduced nearly to a 30% of its expected performance. Under these circumstances, the load voltage is also decremented up to a 20 %. Conversely, in the PS topology, the variations of the C_1's capacitance do not alter the load voltage. However, the efficiency is reduced but with a lower rate than in the SP topology.

An opposite behavior for the load voltage is observed for the deviations of C_2, as illustrated in Fig. 4 and 5. Concerning the efficiency, the variations of C_2 when it is in parallel provoke lower consequences than when it is in series.

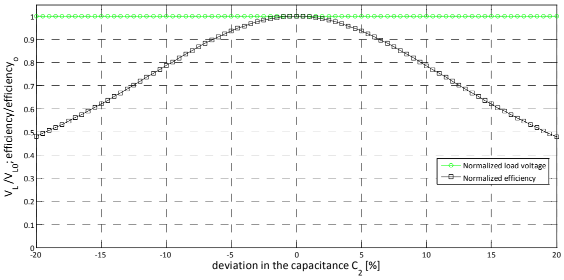

Figure 4. Variation of C_2's capacitance for the SP compensation topology.

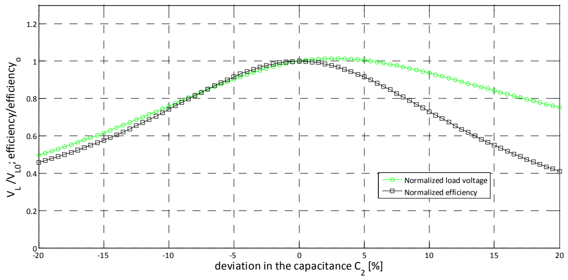

Figure 5. Variation of C_2’s capacitance for the PS compensation topology.

Fig. 6 and 7 depict the effects of varying the self-inductance of L_1 for the SP and PS respectively. Modifications of the primary inductance provoke a decrement of the system efficiency. Diminishing of 10% of this inductance makes the efficiency be reduced up to a 30% in the SP topology and a 20% in the PS topology. As previously analyzed, the deviations in the capacitances lead to a decrement in the load voltage. This effect is also present when the primary coil is modified but only if it in series with C_1. The PS topology illustrates how the load voltage is incremented when the primary coil has a lower inductance. The behavior of varying L_1’s inductance is asymmetrical in the PS topology.

Fig. 8 and 9 illustrate the impact of varying the self-inductance of L_2 for the SP and PS respectively. Similarly to the previous analysis, the variations of the inductance which is in parallel with the capacitance is associated to an incremented load voltage. However, for the SP topology, this occurs when the secondary inductance is increased. Under these circumstances, the efficiency is drastically degraded for the PS topology.

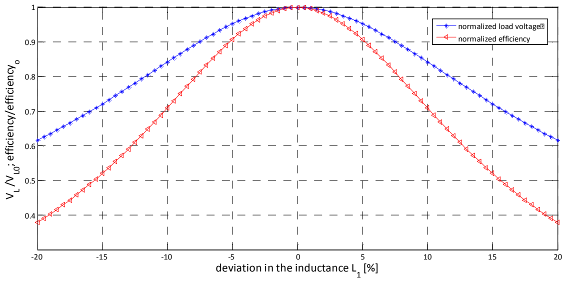

Figure 6. Variation of L_1’s inductance for the SP compensation topology.

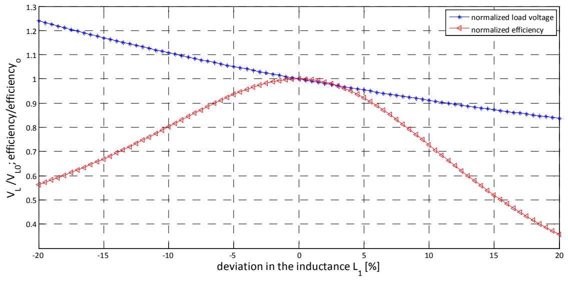

Figure 7. Variation of L_1’s inductance for the PS compensation topology.

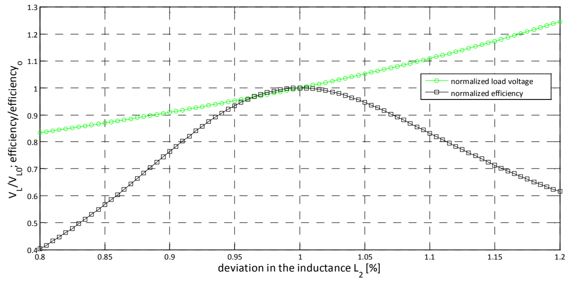

Figure 8. Variation of L_2’s inductance for the SP compensation topology.

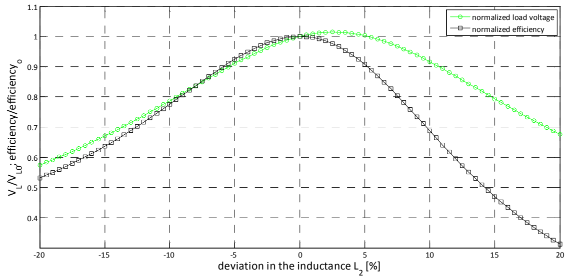

Figure 9. Variation of L_2’s inductance for the PS compensation topology.

Concerning the resistance associated to the coils, there are minor effects when the primary coil has a different resistance as shown in Fig. 10 an 11. This behavior is similar for both compensation topologies studied in this paper. The main difference is that the SP topology also produces variations of the normalized load voltage. An opposite behavior is shown in Fig. 12 and 13 when the deviations of the resistance associated to the secondary coil are analyzed.

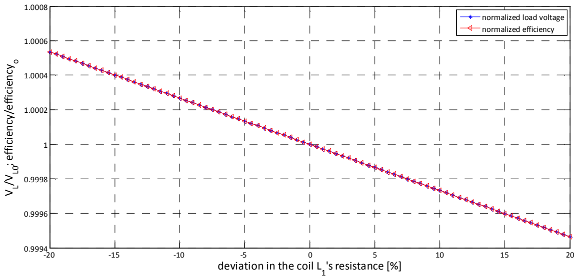

Figure 10. Variation of L_1’s resistance for the SP compensation topology.

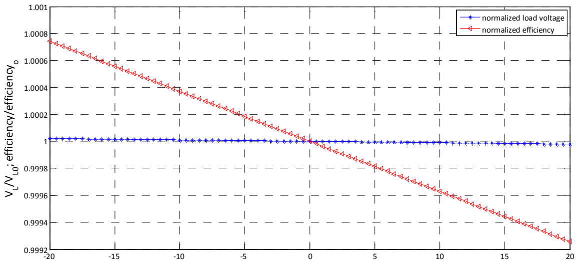

Figure 11. Variation of L_1’s resistance for the PS compensation topology.

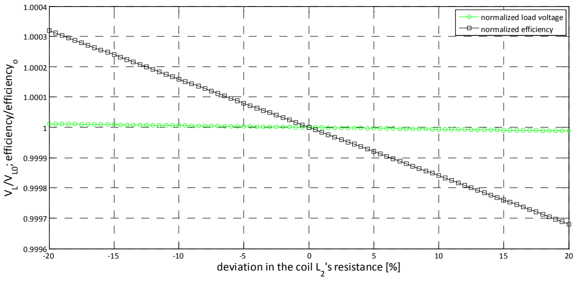

Figure 12. Variation of L_2's resistance for the SP compensation topology.

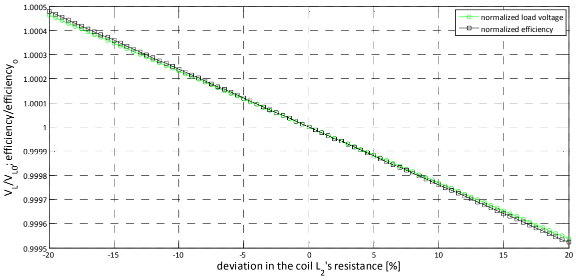

Figure 13. Variation of L_2's resistance for the PS compensation topology.

In the former four figures, we can see that the variations in the studied range do not significantly impact on the system performance.

From the previous analysis, we can conclude that the variations of the inductance and the capacitance when it is in series with its resonant component are more severe than when they are connected in parallel.

V. CONCLUSIONS

ICPT systems are foreseen as the key to promote the use of electric vehicles. The core of an ICPT is two coupled coils with compensation systems to maximize the power transferred to the battery. This paper analyses the sensitivity of an ICPT system to variations in the components' value. The results show that the deviations of the values associated to the components of the resonant tank that are in series greatly impact on the system performance. This evaluation has been conducted in terms of the system efficiency and the load voltage. Two main single-resonant compensation topologies (SP and PS) have been considered in this study.

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