Transmitter Side Control of a Wireless EV Charger Employing IoT

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ABSTRACT

This paper presents a transmitter side control scheme for a series-series compensated wireless power transfer (SS-WPT) system for electric vehicle (EV) charging applications. The proposed control scheme matches the reflected load impedance, by controlling accordingly the front-end dc-dc converter (FEC) of the SS-WPT system. The proposed control scheme drives the FEC, through an optimizer which takes into account the misalignment but also the operational conditions of the system to achieve high efficiency throughout the entire charging process – regardless the EV type, the misalignment conditions or the on-board charger. The novelty of the proposed optimizer lies upon its universal characteristic, which makes it compatible to various SS-WPT topologies. As such, the proposed charging concept is a universal solution, which optimizes the system efficiency regardless the receiver side on-board charger topology (single-stage or double-stage), technical characteristics or control scheme that implements the charging profile. Finally, for the necessary communication between the transmitter and the receiver sides, the Internet of Things (IoT) is employed, offering a low-cost and flexible solution that overcomes compatibility problems between wireless antennas. Simulation and experimental results validate the feasibility of the proposed control scheme, highlighting the efficacy of the proposed wireless charging process.

INDEX TERMS

Battery chargers, impedance matching, inductive charging, Internet of Things, wireless power transmission.

I. INTRODUCTION

Wireless power transfer (WPT) has been recently in the spotlight of various battery charging applications, transferring power from a few watts, such as in biomedical implants [1], cell phones [2] and other consumer electronics [3] applications, to tens of kilowatts, such as in automotive [4]–[6] and robotics [7]. Regarding the Electric Vehicles (EVs), wireless charging offers a more convenient, safe and user-friendly charging process, with lower maintenance costs due to the absence of moving mechanical parts [6]. In this regard, the incorporation of wireless charging for EVs can be a step towards their establishment to the market.

However, designing a wireless charging system might be challenging, because of the poor and uncertain coupling coefficient [8], [9]. The charging profile of the battery also raises significant challenges to optimize the system efficiency over the entire battery charging process, as the load continuously changes [10]–[13]. Therefore, a WPT that is optimized at a particular coupling coefficient and a particular load, will suffer an overall poor performance, as maximum efficiency cannot be achieved in every operating point and coupling coefficient value.

A solution to this problem is the transmitter-side modulation. According to the best of the Authors knowledge, transmitter-side modulation can be classified into two main options; the first one is to use the WPT inverter itself, while the second option is to use an additional front-end dc-dc converter (FEC). Considering the former option, power injection at transmitter side can be simply implemented by the existing WPT inverter through phase-shift modulation (PSM) [9], [14]–[16]. However, this solution suffers from...
small modulation depth in order to keep soft-switching transitions for the inverter circuit [17]. The works in [18]–[20] show that WPT systems can achieve an optimal efficiency, but they suffer from high losses due to hard switching at the inverter and active rectifier stages. The modulation depth can be increased when a FEC is incorporated to the WPT system to regulate the active power transfer [21], forming the second option for transmitter side modulation. Inevitably, this extra power stage is an additional source of power losses; however, the study by Li et al. [22] has shown that a WPT system that incorporates a FEC can achieve higher overall efficiency compared to a WPT system with a frequency modulated inverter. In the majority of works, the efficiency optimization is not decoupled from the receiver side and depends strongly on the on-board charger features, such as the technical characteristics and the control algorithm. For example, the works in [9], [14], [15] use a single-stage active rectifier which participates in efficiency optimization through properly adjusting the equivalent load impedance or the ac-current and voltage ratio. Similarly, the works in [5], [12], [13], [16], [22] use a double-stage passive rectifier and a back-end dc-dc converter (BEC) which adjust the equivalent load impedance seen by the rectifier. Therefore, it becomes difficult to achieve output current/voltage regulation that is required by the battery charging profile and optimized efficiency at the same time. Having the on-board charger responsible for the battery charging profile, optimization should be decoupled from the receiver side.

If the efficiency optimization process is decoupled from the receiver, then the WPT system can operate always at the optimal load impedance point under soft switching at the inverter stage with the aid of a maximum efficiency tracking (MET) algorithm. Several MET algorithms have been studied in [12], [22], [23] whereas other control schemes that either include minimum input current tracking or voltage ratio control are reported in [13] and [21], respectively. The majority of MET control schemes that have been studied so far are based on the perturbation and observation (P&O) or on the system power or efficiency [12], [13], [22], [24]. P&O-based control schemes are inherently slow, due to the uncertainties of perturbation speed and amplitude, but they seem to be adequate for charging applications where the dynamics are slow. Finally, there are some alternative control schemes with faster dynamic response that are based on real-time communication, such as the one proposed in [21]. However, fast dynamic response is not necessary for EV charging applications, with slow dynamics.

As regards WPT systems with impedance matching control for maximum system efficiency, the optimal value of the reflected impedance corresponds to a specific coupling coefficient as well as the resistance values of transmitter and receiver side. However, the coupling coefficient is not fixed in wireless charging systems. On the contrary, it strongly depends on the placement of the EV over the charging pad. Thus, if misalignment is not considered, the optimization method becomes less effective, which may even cause charging failure. Furthermore, the resistance values of transmitter and receiver side may vary during operation due to temperature rise. The majority of works that include MET algorithms without communication, either they don’t consider any notable misalignment deviations [9], [23] or their performance depends strongly on the receiver side technical specifications [13], [16], [22]; the P&O-based MET scheme without communication (between the transmitter and the receiver that has been proposed in [13]), seems to be a particularly appealing scheme for low power applications (where the communication burdens the total cost as well as the power consumption). Although cost effective and simple, this MET scheme cannot be easily designed for a variety of on-board chargers and misalignment conditions.

In order to achieve a misalignment tolerant and universal wireless charger over a (relatively wide) misalignment range, with maximum energy efficiency, a wireless data feedback from the receiver to the transmitter side is required for the regulation of the output power [2], [12], [21], [22], [25]. As regards the wireless communication, the information from the receiver side to the transmitter one can be sent either via radio-frequency (RF) systems (i.e. antennas) [1], [4], [12], [22], [26], or by the aid of standard communication protocols (i.e. “Qi”, “2.4G” or “Bluetooth”) [2], [21], [25]. The study by Fu et al. [12] uses a RF power detector to transmit the necessary information to the receiver side dc-dc converter, in order to achieve high overall system efficiency when variations occur in the relative positioning of coils and load characteristics. However, these RF systems may suffer from compatibility issues (in case of universal charger units that accommodate various commercial EV types), if the transmitter and receiver sides do not incorporate the same communication protocols [25]. In addition, the study by Huang et al. [21] presents a WPT system that comprises FEC and BEC with a coupling coefficient-independent input-to-output transfer function and operation under maximum efficiency. However, it uses fast wireless communication protocols (i.e. 2.4G), which are unnecessary for charging applications with slow dynamics. This is also valid for any real-time based communication method. An alternative solution for dual-side communication in WPT systems is the use of Internet of Things (IoT), as proposed in [27], [28]. The incorporation of IoT in WPT systems advantages over conventional communication ways, as it offers wider connectivity, advanced sensing/actuating, information processing and greater flexibility [27]. Moreover, IoT is a simple, near real-time, cost-effective, flexible and compatible with the smart city concept communication infrastructure [29]; in more details, IoT technology enables the fast sharing of the available information between smart city components, as well as its access over the whole city area, contributing so to effective Smart City services [29]. For example, the use of IoT in a smart grid, which is a vital part of the Smart City concept, can support demand-response of energy use, dispatch power generation for solar panels and wind turbines and facilitate point-of-sale transactional...
services for EVs [29]. Consequently, the IoT can facilitate the communication between the transmitter and the receiver sides in wireless EV charging applications, where the receiver side of the wireless charger is placed on board and the transmitter side is installed underground.

The novelty and contribution of this work lies on the proposed control scheme of the optimizer, which continuously matches the equivalent load impedance with its optimum value throughout the whole charging process (with no need for real-time communication between transmitter/receiver sides), achieving so maximum efficiency regardless of:

1) receiver side on-board charger (single-stage or double-stage, technical characteristics, and battery unit under charge),
2) misalignment conditions,
3) operational conditions.

In addition, the aid of IoT for the transmission of the necessary information from the receiver side to the transmitter one is also a contribution of the current work. The proposed transmitter side control scheme matches the equivalent load impedance with its optimum value, which is related to the coupling coefficient, load characteristics (charging voltage/current) and operational conditions. The detection of the optimal load impedance (in order to maximize the overall efficiency) is based on the tracking of the minimum input current (at the transmitter side) by means of a P&O-based algorithm and the aid of IoT. As such, IoT aids at keeping system operation at the optimal efficiency point, without losing the soft switching property of the inverter (over a wide load range during charging) nor jeopardizing the charging process implementation (charging failures). At the same time, it offers a universal solution for stationary wireless charging applications. Finally, in the current work, the series-series (SS) compensating method is selected, being rather advantageous for battery charging applications [9], [11], [21]. The major characteristic of this compensation topology is that the selection of compensation capacitances is independent of the load or the magnetic coupling [5], [16] [21]. Consequently, the resonant frequency is constant if no major components tolerances are present in the system.

II. SYSTEM DESCRIPTION

A block diagram of the wireless charging system is shown in Fig. 1; it consists of two parts, i.e. the transmitter (installed at the charging station underground) and the receiver (installed on board). The transmitter side consists of the compensation network, the H-bridge inverter, which operates close to the WPT system resonance frequency (constant switching frequency operation) minimizing so power losses [30], and the FEC, which regulates the active transferred power (according to the proposed control scheme). At the receiver side there is a compensating network and the on-board charger, which acts as the interface between the WPT system and the battery and it is responsible for the battery charging profile. The on-board charger may consist either of a single-stage, or a double-stage power conversion. A popular way is a double-stage on-board charger, which commonly includes a passive rectifier and a BEC [5], [12], [13], [16], [22]. However, the single-stage on-board chargers are also an adequate solution. In this case, an active rectifier or a H-Bridge converter (for bidirectional operation) is incorporated on the receiver side to properly control the battery charging. Fig. 2 illustrates the classification among the various on-board charger topologies. In any case, the proposed optimization control scheme is valid independently of the on-board charger at the receiver side (single-stage or double stage, topology and control loop).

As it has been already discussed, in wireless EV charging applications the coupling coefficient varies because of the unavoidable deviations in EV positioning with regard to the charging pad. Thus, the information of the coupling coefficient is necessary for the transmitter-side controller to adjust the active transferred power appropriately. To achieve this, in this work the transmission of the appropriate information of the receiver side is proposed to be implemented by employing IoT. As such, the coupling coefficient (and hence the
mutual inductance of the coils) can be calculated on-fly by the proposed controller, by acquisitioning both the transmitter and the receiver side voltage and current measurements [31]. As depicted in Fig. 1, the receiver side ac measurements are transmitted to the controller of the FEC by means of IoT, for active power regulation and/or optimization according to the alterations on the battery power demands. It is noted that the measurements of current and voltage on the receiver side can also be performed at the dc side of the EV battery. However, in this case, the phase angle of on-board charger is required for accurate charging power calculation (phase angle is zero in case of a passive rectifier). These measurements (ac or dc) are necessary only for the on-fly calculation of coupling coefficient, as well as the transmitter and receiver side equivalent resistances, to properly adjust the optimization operating point. As such, the transmitting frequency can be relatively slow, without compromising the optimizer efficacy (due to the slow dynamics of charging applications).

In block diagram of Fig. 1, $V_{in}$ stands for the DC input voltage; $L_1, L_2$ are the self-inductances of the transmitter and the receiver windings; $M$ is the mutual inductance between the two windings; and $C_1, C_2$ denote the compensating capacitors. It is noted that resistors $r_1, r_2$ stand for total losses of the transmitter and the receiver coil, respectively (i.e. inductors copper losses and capacitors equivalent series resistance, ESR, losses). Finally, $V_o$ stands for the charging voltage.

Both transmitter and receiver windings along with the series connected compensating capacitors are selected to resonate at the same angular frequency, given by

$$\omega_r = \omega_1 = \omega_2 = \frac{1}{2\pi f_o} \sqrt{\frac{1}{L_1C_1} + \frac{1}{\sqrt{L_2C_2}}} \quad (1)$$

As it has been already discussed, the operating frequency $f_o$ of the full-bridge inverter is selected to be equal to $f_r$, in order to ensure soft switching transitions. The coupling coefficient $k$ is calculated by the following expression:

$$k = \frac{M}{\sqrt{L_1L_2}} \quad (2)$$

**A. OPTIMAL LOAD MATCHING CONDITION**

The equivalent circuit of the SS-WPT system under study is shown in Fig. 3, using first-harmonic order approximation. This model is sufficiently accurate for high-quality resonant circuits operating near their resonance approximations. This model is sufficiently accurate for study is shown in Fig. 3, using first-harmonic order approximations.

The series resistance $R_1$ represents the sum of the conduction losses at the transmitter coil and the inverter. As such, the resistance $R_1$ can be interpreted as the sum of two resistances, $r_1$ and $r_{inv}$, which represent the transmitter and inverter losses, respectively. On the other side, the series resistance $R_2$ includes only the conduction losses at the receiver coil $r_2$, whereas the conduction losses at the on-board charger stage are included in the $R_{eq}$. Concluding, the series resistances $R_1$ and $R_2$ can be summarized as follows:

$$R_1 = r_1 + r_{inv} \quad (4)$$
$$R_2 = r_2 \quad (5)$$

where $r_{inv} = 2 \times R_{DSon} \quad (R_{DSon}$ corresponds to drain-source on-state resistance of MOSFET, switching losses are low due to soft switching conditions). Initial values of $r_1$ and $r_2$ can be either measured or calculated from the corresponding datasheets.

Applying circuit analysis at the receiver side of Fig. 3, the following expression is derived:

$$\text{\mid j} \omega M \mid \text{\mid I}_1 \mid = \text{\mid I}_2 \mid (R_2 + R_{eq}) + j(\omega L_2 - \frac{1}{\omega C_2}) \quad \text{\mid \mid 6 \mid}$$

Considering the RMS values of transmitter and receiver currents in (8), the following expression is concluded:

$$\omega M I_{1rms} = I_{2rms} \sqrt{(R_2 + R_{eq})^2 + (\omega L_2 - \frac{1}{\omega C_2})^2} \quad (7)$$

Under resonance operation, the transmitter and receiver currents have only active components. Hence, (7) can be rewritten as:

$$\omega M I_{1rms} = I_{2rms}(R_2 + R_{eq}) \Rightarrow I_{1rms} = \frac{R_2 + R_{eq}}{\omega M} I_{2rms} \quad (8)$$

Next, power transfer efficiency can be expressed as follows:

$$\eta = \frac{I_{2rms}^2 R_{eq}}{I_{1rms}^2 R_1 + I_{2rms}^2 (R_2 + R_{eq})} \quad (9)$$

Combining (8) and (9), the design condition for maximum efficiency under any operating point is achieved when:

$$\frac{\partial \eta}{\partial R_{eq}} = 0 \Rightarrow R_{eq} = \frac{\sqrt{R_2^2 R_1 + \omega^2 M^2}}{\sqrt{R_1}} \quad (10)$$
However, $R_1 R_2 \ll \omega^2 M^2$ so (10) can be simplified to:

$$R_{eq} \approx \omega M \sqrt{\frac{R_2}{R_1}}$$  \hspace{1cm} (11)

Equation (11) shows that the theoretical load matching condition that maximizes the efficiency depends strongly on the SS-WPT system operational characteristics. Those are, the operating frequency $f_o$, the mutual inductance between the transmitter and receiver coils, $M$, and the square root ratio of series resistances, $R_1$ and $R_2$. These parameters (besides the operating frequency of the SS-WPT system which can be considered as constant) may alter the value of $R_{eq}$ during operation, due to uncertainties and changes in their values. For example, $R_{eq}$ is subjected to changes in regular basis as a result of the different $M$ values (imposed by the different coil designs of the various EV types and by the vehicle positioning in regard to the charging pad) and deviations on the series resistances of transmitter and receiver sides. $R_1$ and $R_2$ may also vary during a charging cycle due to temperature rise, as it will be discussed onwards in Section II-C. At this point we would like to highlight that both the mutual inductance ($M$) and the $R_1$, $R_2$ information that is crucial for the operation of the proposed scheme, can be obtained on the fly with the aid of IoT.

**B. MODELING AND CONTROL OF THE FRONT-END CONVERTER**

The output transferred power can be controlled by properly regulating the transmitter and receiver sides dc voltages, $V_1$ and $V_2$, according to the following equation [5], [31]:

$$P_{out} = \frac{8}{\pi^2} \frac{V_1 V_2}{\omega M}$$  \hspace{1cm} (12)

However, $V_1$ is controlled by the FEC and it strongly depends on the equivalent impedance that is reflected at the input stage of the HF inverter. In other words, $V_1$ can be expressed as

$$V_1 = I_1 Z_{inv,dc},$$  \hspace{1cm} (13)

where $I_1$ is the output dc current of the FEC and $Z_{inv,dc}$ is the equivalent impedance reduced at the input stage of the HF inverter.

The equivalent circuit of Fig. 3 can be further analyzed if the current-dependent source, $-j\omega M I_2$, is replaced by an equivalent impedance $Z_{ref}$, the magnitude of which is calculated by:

$$|Z_{ref}| = \frac{|-j\omega M I_2|}{I_1}$$  \hspace{1cm} (14)

Considering the RMS values of transmitter and receiver currents and substituting (8) into (14):

$$Z_{ref,\text{rms}} = \frac{\omega M I_{2,\text{rms}}}{I_{1,\text{rms}}} = \frac{\omega M I_{2,\text{rms}}}{\frac{R_2 + R_{eq}}{\omega M} I_{2,\text{rms}}} = \frac{\omega^2 M^2}{R_2 + R_{eq}}$$  \hspace{1cm} (15)

According to Fig. 4a, the RMS value of the WPT inverter output voltage is given by

$$V_{inv,\text{rms}} = I_1,\text{rms} \left[ R_1 + j \left( \omega L_1 - \frac{1}{\omega C_1} \right) + \frac{\omega^2 M^2}{R_2 + R_{eq}} \right]$$  \hspace{1cm} (16)

Assuming operation close to resonance, (16) is rewritten as:

$$V_{inv,\text{rms}} = I_1,\text{rms} \left( R_1 + \frac{\omega^2 M^2}{R_2 + R_{eq}} \right)$$  \hspace{1cm} (17)

So, the equivalent impedance at the inverter input stage, as shown in Fig. 4b, becomes:

$$Z_{inv,\text{dc}} = \frac{\pi^2 V_{inv,\text{rms}}}{8 I_{1,\text{rms}}} = \frac{\pi^2}{8} \left( R_1 + \frac{\omega^2 M^2}{R_2 + R_{eq}} \right)$$  \hspace{1cm} (18)

Hence, $V_1$ can be replaced by the product of the dc current $I_1$ and the equivalent impedance $Z_{inv,\text{dc}}$. So, (12) can be rewritten as:

$$P_{out} = \frac{8}{\pi^2} \frac{I_1 Z_{inv,\text{dc}} V_2}{\omega M}$$  \hspace{1cm} (19)

According to (12) and (19), the output transferred power can be controlled either directly by properly varying the output dc voltage of FEC or indirectly by properly varying the output dc current of FEC. It is noted that both control options result in a SS-WPT system with excellent partial load behavior. However, each one is characterized by pros and cons. In more details, a current control scheme at the FEC side is more suitable when a fast charging control loop is implemented at the receiver side, whereas real time overcurrent protection is provided to the system. On the contrary, a voltage control loop is of more universal nature and thus applicable in any case.

So, the scope of the voltage/current control on the FEC is to keep the optimal load impedance, regardless the EV battery power demand, misalignment conditions and $R_1 - R_2$ variation, by properly varying either the output dc voltage or current. The optimal load impedance reference is given by combining (11) and (18):

$$Z_{\text{ref,dc}} = \frac{\pi^2}{8} \left( R_1 + \frac{\omega^2 M^2}{R_2 + \omega M \sqrt{\frac{R_2}{R_1}}} \right)$$  \hspace{1cm} (20)

Hence, working on (12) and (19), the voltage and current reference of the FEC is given by:

$$V_{\text{ref}} = V_1 \left( Z_{\text{inv,dc}} = Z_{\text{ref,dc}} \right) = \frac{\pi^2}{8} \frac{P_{out} \omega M}{V_2}$$  \hspace{1cm} (21)
\[ I_{\text{ref}} = I_1 \left( Z_{\text{inv}, \text{dc}} \triangleq Z_{\text{ref}, \text{dc}} \right) = \frac{\pi^2}{8} \frac{P_{\text{out}} \omega M}{Z_{\text{ref}, \text{dc}} V_2} \] (22)

At this point it is worth noting that (20) is the core equation of the proposed control scheme, regardless if voltage or current control is applied on the FEC. Based on this equation, we will build the optimizing algorithm to control optimally the WPT system through the FEC. As a result, the SS-WPT system will feature an excellent partial load behavior, maintaining high efficiency throughout the charging process. The boundary operating conditions of the system are limited by \( V_{\text{ref}} \) and \( I_{\text{ref}} \) and their direct correlation with the induced voltage at the transmitter side \((-j\omega M I_2)\) and at the receiver side \((j\omega M I_1)\) respectively. Hence, as for \( V_{\text{ref}} \), its rms value should be kept equal or above the induced voltage \((-j\omega M I_2)\) to meet power flow direction. Similarly, \( I_{\text{ref}} \) should be equal or above the rms value of \( V_{\text{rec}} \). These limitations in voltage and current references can be expressed as:

\[
|V_{\text{inv}, \text{rms}}| \geq |-j\omega M I_{2, \text{rms}}| \Rightarrow V_{\text{ref}} \geq \frac{\pi^2}{8} \frac{\omega M I_o}{2} \quad (23)
\]

\[
|j\omega M I_{1, \text{rms}}| \geq |V_{\text{rec}, \text{rms}}| \Rightarrow I_{\text{ref}} \geq \frac{8}{\pi^2 \omega M} \frac{V_2}{2} \quad (24)
\]

Hence, according to (23) and (24), the transmitter side control scheme limits its voltage or current reference to this threshold, regardless if the load is still decreasing.

C. SENSITIVITY ANALYSIS OF OPTIMAL LOAD IMPEDANCE

In subsection II-A, we reached to the conclusion that \( R_{eq} \) is strongly affected by the operating conditions, because of its dependency on the system mutual inductance \( M \) and series resistances \( R_1 \) and \( R_2 \). As the optimal load impedance reference, \( Z_{\text{ref}, \text{dc}} \), depends also on \( R_{eq} \), it should be subjected to the same dependencies. The mutual inductance, however, it is not expected to change during the charging process (the EV stands above the charging pad), and thus the only sources of uncertainty in (20) are the \( R_1 \) and \( R_2 \) values. As already discussed in subsection II-A, the values of \( R_1 \) and \( R_2 \) may vary upon system design and operating conditions. In other words, \( R_1 \) and \( R_2 \) may change during operation due to the temperature rise on the transmitter and the receiver sides. For these reasons, a sensitivity analysis is performed to investigate the impact of \( R_1 \) and \( R_2 \) on the optimal load impedance reference value when the above resistances are not calculated on the fly. Fig. 5 presents the p.u. variation of optimal load impedance \( Z_{\text{ref}, \text{dc}} \). It is worth noting that the three-dimensional plot of \( Z_{\text{ref}, \text{dc}} \) corresponds to three different cases, i.e. the under study system design, a 6.6 kW WPT system design as described in [4] and a 50 kW WPT system design as described in [32]. The variation range of \( R_1 \) and \( R_2 \) is selected to be between 0.1 p.u. and 2 p.u., according to the typical resistance values found in literature [9], [12], [16], [22]. As highlighted in the three-dimensional plot of \( Z_{\text{ref}, \text{dc}} \), the optimal load impedance reference can become more than four times higher than the base value, if significant deviations in series resistances \( R_1 \) and \( R_2 \) values occur, highlighting the need for online information on the actual values of \( R_1 \) and \( R_2 \), in order to accurately calculate the \( Z_{\text{ref}, \text{dc}} \) value. The operational characteristics of each system are presented in Table 1 as well as the base values of \( R_1 \), \( R_2 \) and \( Z_{\text{ref}, \text{dc}} \). It is noted that the base value of \( Z_{\text{ref}, \text{dc}} \) is calculated from (11) and (20), assuming that \( R_1 = R_2 \).

D. THE ROLE OF IOT

As described in Section II-B, the optimal load impedance can be achieved by simply measuring the output voltage and current of the FEC. Then, the transmitter side controller modulates the duty cycle of the FEC in order to set the desired \( Z_{\text{inv}, \text{dc}} \) value according to its reference value in (20). It is recalled that the optimal \( Z_{\text{ref}, \text{dc}} \) value in (20) depends on the mutual inductance \( M \) (which reflects the specific coupling conditions) and the series resistances \( R_1 \), \( R_2 \). As it has been already discussed, during a specific charging process the transmitter side controller should be aware of both the specific mutual inductance value \( M \) and the \( R_1 \), \( R_2 \) information in order to calculate the specific optimal load impedance reference value, \( Z_{\text{ref}, \text{dc}} \). Thus, applying this optimal impedance value, maximum efficiency can be achieved throughout any single charging process (within an acceptable range for the misalignment level, i.e. \( \sim 20\% \) [11]. For this purpose, a wireless data feedback is needed from the receiver to the transmitter side, including the rms value of the ac voltage \( V_{\text{rec}, \text{rms}} \) and current \( I_{2, \text{rms}} \). As power variations during the charging process are relatively slow compared to the switching
frequency of the dc-dc converters, the control loop of the FEC can be much faster than the variations of load impedance. As a result, a fast-wireless communication channel is not necessary. In this work, IoT is proposed to implement the wireless communication between the transmitter and receiver sides, offering a flexible and cost-effective solution whilst mitigating any compatibility issues. Combining (3), (11), the online calculation of $M$ value as a function of the receiver voltage and current is concluded:

$$M = \frac{R_{eq}}{\omega} \sqrt{\frac{R_1}{R_2}} = \frac{V_{\text{rec, rms}}}{\omega I_{2, \text{rms}}} \sqrt{\frac{R_1}{R_2}}$$ (25)

The online recalculation of $R_1$ and $R_2$ values is based on power losses analysis. It is noted that the initial values of transmitter and receiver series resistances $R_1$ and $R_2$ are given by (4) and (5). Thus, the power losses of air-core transformer $P_{\text{loss,ACT}}$ will give the exact values of $R_1$ and $R_2$ throughout the charging process, considering, for example, potential deviation from initial values due to temperature rise. So, according to Fig. 1, the power $P_1$ at the inverter input stage can be expressed as:

$$P_1 = P_{\text{loss,inv}} + P_{\text{loss,ACT}} + P_2$$ (26)

Hence, from (26) the power losses of air-core transformer can be calculated as follows:

$$P_{\text{loss,ACT}} = V_1 I_1 - V_{\text{rec, rms}} I_{2, \text{rms}} - \frac{\pi^2}{4} I_1^2 R_{\text{DSon}}$$ (27)

Assuming uniformly loss distribution at transmitter and receiver sides, the $R_1$ and $R_2$ values can be recalculated as follows:

$$I_{1, \text{rms}} R_1 \approx I_{2, \text{rms}} R_2 \approx \frac{P_{\text{loss,ACT}}}{2}$$

$$\Rightarrow R_1 = \frac{4}{\pi^2} \frac{P_{\text{loss,ACT}}}{I_1^2} \text{ and } R_2 = \frac{P_{\text{loss,ACT}}}{I_{2, \text{rms}}}$$ (28)

It is worth noting that within the iterative searching process of maximum energy efficiency (MEE) point, the on-board charger regulates the charging current or voltage, setting so the specific load power value, $P_{\text{out}}$, for the SS-WPT system. Consequently, under any specific $P_{\text{out}}$, when the minimum input dc current $I_1$ or voltage $V_1$ is reached, maximum efficiency is achieved.

The flowchart of this approach is depicted in Fig. 6 and described as follows:

1) An initial value of front-end voltage/current reference, $V_{\text{ref0}}/I_{\text{ref0}}$, is applied. This voltage/current value should be high enough to meet the maximum power rating of the load. Additionally, the minimum and maximum acceptable voltage/current reference $V_{\text{ref(min)}}/I_{\text{ref(min)}}$ and $V_{\text{ref(max)}}/I_{\text{ref(max)}}$ as well as the values of transmitter and receiver winding resistances and ESRs, $r_1$ and $r_2$, are set. The values of $R_{\text{DSon}}$ is also set. An initial value of load impedance reference $Z_{\text{ref0}}$, corresponding to the nominal coupling coefficient, is applied.

2) The input voltage and current at on-board charger stage, $V_{\text{rec}}$, $i_2$, are measured and transmitted to the transmitter side through IoT. The equivalent impedance $Z_{\text{inv,dc}}$ is also measured.

3) The initial values of $R_1$ and $R_2$ are calculated according to (4) and (5) respectively.

4) Next, according to (25) the value of mutual inductance, $M$, is calculated. Hence, using (20), an initial value of $Z_{\text{inv,dc}}$, corresponding to this specific coupling coefficient, is calculated. It is noted that the calculation of $M$ is performed only once during a single charging process, since the EV is parked.

5) The value of $Z_{\text{ref,dc}}$, as well as the initial value of voltage/current reference, $V_{\text{ref0}}/I_{\text{ref0}}$, are applied.

6) An iterative procedure begins and the values of $V_{\text{rec, rms}}, I_{2, \text{rms}}$, and $Z_{\text{inv,dc}}$ are measured.

7) During operation, the values of $R_1$ and $R_2$ may change. So, they are recalculated according to (28), resulting to a new value for $Z_{\text{ref,dc}}$. This procedure is periodically executed every $T_{d1}$.

8) After this time interval, $T_{d1}$, a new calculation process will start in case that the values of $R_1$ and $R_2$ have changed.

9) At the same time, in every step (n-step) the voltage/current reference, $V_{\text{ref(n)}}/I_{\text{ref(n)}}$, increases (or decreases) slightly (e.g. $\Delta V = 2\% \ V_{\text{ref0}} / \Delta I = 2\% \ I_{\text{ref0}}$) to a new value, $V_{\text{ref(n)}} = V_{\text{ref(n-1)}} + \Delta V / I_{\text{ref(n-1)}} = I_{\text{ref(n-1)}} + \Delta I$ (or $V_{\text{ref(n)}} = V_{\text{ref(n-1)}} - \Delta V / I_{\text{ref(n-1)}} = I_{\text{ref(n-1)}} - \Delta I$) through a P&O procedure. Changing the FEC voltage or current reference will change $V_1$ (either directly or indirectly) and subsequently the value of $Z_{\text{inv,dc}}$, according to (13).

10) The comparison among $Z_{\text{inv,dc}}$ and $Z_{\text{ref,dc}}$ is performed. If $Z_{\text{inv,dc}}$ is smaller than 0.95 $Z_{\text{ref,dc}}$ (i.e. the available power is more than the requested amount) or if $Z_{\text{inv,dc}}$ is higher than...
1.05\times Z_{\text{ref, dc}} (i.e. the available power is less than the requested amount), then step 9 is repeated accordingly, until \( Z_{\text{inv, dc}} \) enters \( Z_{\text{ref, dc}} \) zone. Then, the maximum energy efficiency point has been reached.

11) Compare \( V_{\text{ref}}/I_{\text{ref}} \) with the minimum voltage/current reference \( V_{\text{ref}}(\text{min})/I_{\text{ref}}(\text{min}) \) that keeps the power flow direction. If \( V_{\text{ref}}(\text{ref}) \) is less than \( V_{\text{ref}}(\text{min})/I_{\text{ref}}(\text{min}) \), then \( V_{\text{ref}}(\text{ref})/I_{\text{ref}}(\text{ref}) = V_{\text{ref}}(\text{min})/I_{\text{ref}}(\text{min}) \).

12) Compare \( V_{\text{ref}}(\text{ref})/I_{\text{ref}}(\text{ref}) \) with the maximum voltage/current reference \( V_{\text{ref}}(\text{max})/I_{\text{ref}}(\text{max}) \). If \( V_{\text{ref}}(\text{ref})/I_{\text{ref}}(\text{ref}) \) is higher than \( V_{\text{ref}}(\text{max})/I_{\text{ref}}(\text{max}) \), then \( V_{\text{ref}}(\text{ref})/I_{\text{ref}}(\text{ref}) = V_{\text{ref}}(\text{max})/I_{\text{ref}}(\text{max}) \).

13) The optimum operation point will be kept for a predefined time interval \( T_{d2} \).

14) After this time interval, \( T_{d2} \), a new searching process will start from this operating point in case that the load has changed.

### III. SIMULATION RESULTS

Simulation studies are conducted using the software platform MATLAB/Simulink to evaluate the performance of the proposed transmitter side control scheme implementing a typical lithium-ion (Li-ion) battery charging profile, as depicted in Fig. 7. Typical voltage levels of EVs Li-ion batteries range between 250 V – 400 V, depending upon the capacity of each battery pack, the number of cells included etc. [33]. However, in our work, an under-scale battery voltage pack of 96 V is assumed for the simulation and experimental study. Considering a small variation between charge voltage threshold and discharge voltage cutoff for 96V battery voltage, this battery is emulated with a constant voltage at simulation setup [33]. The dc input voltage on the transmitter side is 325 V, emulating so the rectified single-phase voltage level.

In order to thoroughly evaluate the universal characteristics of the proposed transmitter side control scheme, the simulation model has been built considering two alternative design options for the on-board charger. Firstly, we assume a single-stage on-board charger with passive rectifier and BEC (according to the available experimental setup), as depicted in Fig. 14. Then, a single-stage on-board charger (i.e. active rectifier with phase-shift) is examined. The system parameters are given in Table 2, whereas a summary of the charging profile for the simulation as well as for the experimental setup is given in Table 3. It is noted that the simulation model is running for a charging profile of 10 seconds, completing however a charging cycle. The IoT communication, which is used for feedback purposes, is emulated with a time delay to the signals transmitted to transmitter side controller. \( R_1, R_2 \) are calculated online as described in the flowchart of Fig. 6, whereas the initial values of \( R_1 \) and \( R_2 \) (prior to the on-fly calculation) are calculated by (6) and (7). The \( R_1, R_2 \) values are based on the measured parasitic resistances of the transmitter and receiver resonant tank of the experimental setup and are given in Table 2. Finally, misalignment-free operation as well as 20% misaligned coils have been considered in the following simulation tests.

#### TABLE 2. Summary of the wireless EV charger parameters.

| Symbol | Parameter                      | Value  |
|--------|--------------------------------|--------|
| \( L_1 \) | transmitter winding self-inductance | 172.6 \( \mu \)H |
| \( L_2 \) | receiver winding self-inductance | 169.6 \( \mu \)H |
| \( C_1 \) | transmitter resonance capacitance | 15.6 nF |
| \( C_2 \) | receiver resonance capacitance | 15.6 nF |
| \( r_1 \) | transmitter parasitic resistance | 0.47 \( \Omega \) |
| \( r_2 \) | receiver parasitic resistance | 0.46 \( \Omega \) |
| \( M \) | mutual inductance | 34.3 \( \mu \)H |
| \( k \) | coupling coefficient | 0.2 |
| \( f_s \) | resonance frequency | 97.3 kHz |

#### TABLE 3. Summary of the charging profile.

| Symbol | Parameter                      | Simulation | Experimental |
|--------|--------------------------------|------------|--------------|
| \( I_{\text{nom}} \) | rated charging current | 10.65 A | 10.8 A |
| \( I_{\text{min}} \) | minimum charging current | 3 A | 3 A |
| \( V_o \) | battery charging voltage | 96 V | 96 V |
| \( t_o \) | charging time | 10 s | 10 min |

The effectiveness of the proposed algorithm presented in Section II-D, in terms of \( M, R_1, R_2 \) calculation is examined in Fig. 8. The \( M, R_1, R_2 \) values are calculated under nominal coupling conditions (i.e. \( k = 0.2 \)), as well as for 20% misaligned coils (i.e. \( k = 0.16 \)). According to Fig. 8, the calculated \( M \) values are sufficiently close to the actual ones; the reported deviations between calculated and actual values are below 2% for both cases. In addition, the on-fly calculation of \( R_1 \) and \( R_2 \) values according to (28) is also presented in Fig. 8 and stands for both cases. It is noted that these calculated values affect the final value of \( Z_{\text{ref, dc}} \), as discussed in the previous subsection.
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FIGURE 8. On-fly calculation of $M, R_1, R_2$.

A. DOUBLE-STAGE ON-BOARD CHARGER

Next, the simulation model is built with a double-stage on-board charger at the receiver side, according to Fig. 14. The on-board charger includes a passive rectifier and a BEC implementing the battery charging profile. Fig. 9 depicts the dc input and output power of the wireless charger for 96 V battery voltage level. The input power is illustrated comparatively assuming two different cases; case (1) refers to a constant reference at the FEC (current-controlled) for the whole charging process, whereas case (2) refers to the incorporation of the proposed control scheme. In both cases, the simulated mutual inductance corresponds to misalignment-free (perfectly aligned coils) operating conditions. When the proposed control scheme is applied, the SS-WPT system operates at the optimum load impedance point, minimizing so the input current reference for the FEC. It is noted that the output power (i.e. the charging power) is imposed by the applied charging profile, as such is common for both cases.

FIGURE 9. Simulation results of input and output power of the wireless charger throughout the charging profile with (blue line) and without (red line) the proposed control scheme.

According to Fig. 9, in CC charging mode, the input power for the two cases is approximately the same. However, during CV charging mode, the input power curves deviate significantly. This deviation corresponds to the energy savings when the proposed control scheme is incorporated to the wireless charger and it is attributed to the inability of the SS-WPT system to accommodate partial load conditions without the proposed control loop. Concluding, the incorporation of the proposed transmitter side control can save significant amounts of energy. In particular, the shaded area depicted in Fig. 8 corresponds to the energy savings during the under-study charging profile, reducing so the consumption over a charging cycle by 9%. Hence, Fig. 9 validates that high efficiency is maintained for the whole charging process by using the proposed control method.

Next, the proposed control scheme is tested under misaligned conditions. Fig. 10 demonstrates the battery charging power during the whole charging process considering 20% misalignment. The power curve of case (1) refers to the proposed transmitter side control algorithm with online calculation of misalignment, employing feedback information (by means of the incorporated IoT communication), whereas the power curve of case (2) refers to the conventional MET algorithm without communication – considering the nominal coupling among transmitter and receiver sides. It is noted that the load power demand (as indicated by the charging profile) is depicted with the dash line and it is common for both cases. According to these results, the power curve in case (1) follows the charging profile curve, highlighting that the whole charging process is successful. On the other hand, the power curve of case (2) fails to follow the charging profile curve, leading to system failure during the charging process. The system inability to serve the whole charging profile can be explained by the wrong value of the impedance reference $Z_{\text{ref}, \text{dc}}$ that is applied to the transmitter side controller. It is worth noting that the misalignment in case (1) is calculated online in the beginning of the charging process (adapting so the $Z_{\text{ref}, \text{dc}}$ value to the specific coupling conditions), whereas in case (2) the $Z_{\text{ref}, \text{dc}}$ corresponds to the nominal coupling. Consequently, the feedback information (with the proposed incorporation of IoT communication) in the control algorithm establishes a misalignment-tolerant wireless charger, operating under high efficiency during the whole charging process.

B. SINGLE-STAGE ON-BOARD CHARGER

Next, the simulation model is built with a single-stage on-board charger, including a phase-shift active rectifier, as described in [14]. The total configuration of wireless charger setup is depicted in Fig. 11. In this case, the phase-shifted active rectifier controls the output power implementing the battery charging profile. Fig. 12 presents the input voltage and current at the active rectifier stage for an output
power of 600 W approximately (i.e., at the middle of the charging profile). The scope of the single-stage consideration is to validate the universal characteristics of the proposed transmitter side control scheme.

For this purpose, Fig. 13 presents the energy savings for the same cases described in the previous subsection; case (1) refers to a constant reference at the FEC (voltage-controlled) for the whole charging process, whereas case (2) refers to the incorporation of the proposed control scheme. In both cases, the simulated mutual inductance corresponds to misalignment-free (perfectly aligned coils) operating conditions. When the proposed control scheme is applied, the SS-WPT system operates at the optimum load impedance point. It is noted that the output power (i.e., the charging power) is imposed by the applied charging profile, as such is common for both cases. Hence, the incorporation of the proposed transmitter side control can maintain high efficiency for the whole charging process, saving so significant amounts of energy. In particular, the shaded area depicted in Fig. 13 corresponds to the energy savings during the under-study charging profile, reducing so the consumption over a charging cycle by 12%. Concluding, the proposed transmitter side control scheme is valid also with a single-stage on-board charger, offering so a universal solution independent of the receiver side.

IV. EXPERIMENTAL RESULTS

In order to verify the transmitter side controller behavior of the SS-WPT system for two different cases, i.e., fully aligned coils and 20% misaligned coils, an experimental setup has been constructed – rated at 1.1 kW. The loosely coupled (orthogonal) coils of the prototype are made of Litz wire in double D structure (DD). The DD topology is desirable because it offers single sided flux paths and low leakage flux [30], [32]. The dimensions of the transmitter and receiver coils are identical and equal to 400 mm × 450 mm; each coil comprises 24 turns of 2 mm diameter Litz wire. The distance between coils was set at 150 mm, resulting in a measured coupling coefficient value of $k = 0.2$, being in line with real wireless EV charging applications. In addition, I93-cores are utilized for the improvement of the magnetic field distribution. Fig. 14 shows the schematic diagram and the experimental setup of the wireless charger with double-stage on-board charger. The foremost parameters of the SS-WPT experimental setup are summarized in Table 2, whereas the foremost components used in the WPT circuitry are noted in Table 4. For simplicity purposes and in accordance with the simulation model, an electronic load in CV mode is used to emulate the battery voltage level. The front-end and back-end buck converters are controlled at fixed switching frequency via two TMS320F28027 microcontroller units (MCU). The BEC MCU implements the charging profile and transmits the appropriate signals to the WiFi module through its serial communication port, whereas the FEC MCU receives the appropriate signals through its WiFi module and implements the transmitter control algorithm according to the flowchart of Fig. 6. The WiFi modules used for the experimental setup are identical (NodeMCU-ESP8266 WiFi module), whereas the ThingSpeak website is used to upload and download the necessary information.

Fig. 15 presents the measured input power of the wireless charger for two different cases, as well as the charging power.
injected to the electronic load. It is noted that case (1) refers to a constant current reference applied at the FEC, whereas case (2) refers to the proposed control scheme. The current reference applied in case (1) is set at the minimum current reference that meets load demand. The charging power follows the aforementioned charging profile and it is common for both cases. According to Fig. 15, power consumption during CC charging is approximately the same for both cases; however, during CV charging a notable deviation is recorded, as a result of the optimizing procedure regarding $Z_{\text{ref}, \text{dc}}$, which runs throughout the charging process. Therefore, both simulation and experimental results validate that the incorporation of the proposed control scheme can save significant amounts of energy. In particular, the shaded area depicted in Fig. 15 corresponds to the energy savings during a charging cycle, reducing so the consumption by 14%, highlighting once again the notable energy saving that can be achieved by the proposed control method; actually, the energy savings are higher in experimental setup than in the simulation test due to the fact that power losses at FEC and BEC units are higher in the experimental case.

The measured output power that is transferred to the load during the charging process considering 20% misalignment is shown in Fig. 16. Case (1) refers to the proposed transmitter side control algorithm with online calculation of misalignment, employing the IoT communication. On the other hand, case (2) refers to the conventional MET algorithm without communication, considering the nominal coupling among transmitter and receiver sides. The load demand (with respect to the applied charging profile) corresponds to the black solid line. It can be observed that the output power points in case (1) (marked with “+”) follow the charging profile curve, highlighting that the whole charging process is successfully performed. On the other hand, the output power points in case (2) (marked with red solid line) do not follow the charging profile curve, leading to system failure during the charging process. It is recalled that, similar to the corresponding simulation results, an online calculation of $Z_{\text{ref}, \text{dc}}$ value takes place in the beginning of case (1), whereas in case (2) $Z_{\text{ref}, \text{dc}}$ value corresponds to the nominal coupling. Consequently, the experimental results verify the theoretical analysis as well as the simulation outcomes, regarding the fact that the proposed control algorithm establishes a misalignment-tolerant wireless charger, operating under high efficiency during the whole charging process.
TABLE 5. Desirable features of optimization strategies for wireless ev battery charger.

| Desirable feature                                      | [8], [9], [19] | [12], [14], [24] | [13] | [15] | [16] | [18] | [20] | [21], [22] | this work |
|-------------------------------------------------------|----------------|------------------|------|------|------|------|------|------------|-----------|
| independent from on-board charger                     | ×              | ×                | ×    | ×    | ×    | ×    | ×    | ×          | ✓         |
| efficiency optimization for coupling variation        | ×              | ✓                | ✓    | ×    | ×    | ×    | ✓    | ✓          | ✓         |
| no need for real-time communication                   | ✓              | ×                | ✓    | ✓    | ×    | ×    | ×    | ×          | ✓         |
| consideration of $R_L$, $C_L$ variation                | ×              | ×                | ×    | ×    | ×    | ×    | ×    | ×          | ✓         |
| efficiency optimization for a wide load range         | ✓              | ✓                | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          | ✓         |
| soft switching transitions at inverter stage           | ✓              | ✓                | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          | ✓         |

Summarizing, Table 5 presents comparatively some desirable features of optimizing strategies for wireless EV battery chargers developed so far, highlighting the contribution of the current work. In more details, it is desirable to develop a wireless EV battery charger which is a) independent from the on-board charger topology (single-stage or double stage) and battery unit under charge, b) it has optimized efficiency for a wide load range and coupling variation, c) it has soft switching transitions at inverter stage and d) it has no real-time communication requirements.

V. CONCLUSION

In this paper, an improved control algorithm has been proposed for a universal SS-WPT charging system, aiming at efficiency optimization during the whole charging cycle under various misalignment conditions and for various EV types. The proposed transmitter side control scheme is implemented on the front-end converter and is fully independent from the receiver side on-board charger (single-stage or double-stage), the control loop etc. It has been derived and experimentally verified that under every specific coupling coefficient, an optimal load impedance value that maximizes system efficiency, exists. In this context, an optimization algorithm (with no need for real-time communication) that considers misalignment is developed for the tracking of the optimal load impedance. The necessary communication between the transmitter and the receiver side is implemented through IoT, offering a flexible, low-cost, and universal solution whilst avoiding compatibility problems between wireless antennas. Hence, the proposed transmitter side control scheme improves the overall performance of the charging system, as it can be applied under various coupling coefficients and battery charging profiles, whereas considerable energy savings are achieved. A 1.1 kW wireless charger system test bench has been developed, validating the advantages of the proposed (IoT feedback-based) control algorithm.

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