Toward efficient very low frequency wireless power transfer for EVs: From grid to battery

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Abstract. This paper aims to improve the efficiency, affordability, and safety of Wireless Power Transfer (WPT) devices. While wireless inductive charging is common in devices like smartphones, charging electric vehicles presents significant challenges due to high frequency electromagnetic fields that can be dangerous for users and those nearby. Current systems are expensive due to the use of specialized materials and components. By developing WPT systems with drastically reduced frequency levels, this research has the potential to significantly impact the widespread adoption of affordable, safe, and efficient WPT devices for high-power applications like electric vehicle charging. In fact, using lower frequencies allows us to build WPT systems with far less expensive materials, *e.g.* no need of Litz wires and ferrites that can be replaced by single core copper wires and classical magnetic steels. The effectiveness of the method is demonstrated through simulation using MATLAB Simulink® and experimental tests. The results indicate that it is possible to maintain good performance, reduce limitations and costs, and improve user acceptance of WPT systems by considerably lowering the frequency of electromagnetic fields that are classically used in such systems.

Keywords: Wireless energy transfer, Inductive Power Transfer (IPT), Electric Vehicles (EVs), wireless charging system, resonant coupling

1. Introduction

The utilization of Wireless Power Transfer (WPT) devices has risen in popularity over recent years due to their widespread usage in a variety of applications, including smartphones, electric toothbrushes, and electric vehicles (EVs) [1]. Despite significant progresses in the development of electric vehicles, they still come with certain drawbacks, such as high costs and issues related to charging. The primary challenges associated with EV charging are the limited availability of charging stations and the extended charging times required for full battery capacity [2]. There are two primary methods for charging electric vehicles: conductive charging and wireless charging [3,4]. Conductive charging is the mainstream technique due to its efficiency, cost-effectiveness, and electromagnetic compatibility [3,4]. However, the use of Wireless Power Transfer (WPT) chargers for EVs presents a challenge because of (1) the radiated electromagnetic fields that are regulated by various health standards, and (2) the comparison with its wired counterpart in

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terms of efficiency, power and costs. For example, the Society of Automotive Engineers (SAE) has set a standard for resonance frequency at 85 ± 5% kHz for a light-duty passenger vehicle [5]. Additionally, IEEE C-95.1-12345-2014 provides insight into human safety from the high-frequency magnetic field [5]. Furthermore, the use of specific ferrites, Litz wire, and fast power components to operate at high frequencies can make current systems very costly and not competitive with the wired system. Nevertheless, wireless charging is gaining attention due to its convenience, automation, weatherproof capability, and several recent studies have focused on this method [6–10]. The efficiency of the wireless power transfer system is primarily influenced by two critical components: the power electronic converters and a loosely coupled transformer. The weak coupling between the transmitter and receiver pads results in decreased efficiency of the power transfer through the magnetic field. Furthermore, the efficiency of the power electronic converters can also affect the overall efficiency of the WPT system [5,11,12]. The main objective of this paper is to conduct an initial investigation about the technical feasibility of drastically lowering the fundamental frequency of the WPT systems, *i.e.* lower the frequency to a few hundred Hz rather than several kHz, and considering not only the simulation but also experimental verifications. For this first step, the device has not been optimized and, according to the results, this represents future work and opens a research avenue. With this in mind, this paper also shows that the complete device can be made using materials at much lower costs than those used in high frequency counterparts. This paper proposes a WPT system functioning at a frequency of 400 Hz. Compared to high frequency systems, a WPT device operating at few hundred Hertz has some drawbacks, including (1) the decrease in the effectiveness of the magnetic power transfer, and (2) the increase in volume and weight. However, it is also very important to consider the many advantages it offers, *i.e.* the lack of efficiency is likely to be compensated, at least partially, by reducing the power loss in the power electronic converters in order to reach similar global efficiency from the grid to the battery. In fact, considering far lower switching frequencies enable the use of far less expensive transistors, as proposed in this paper. About the volume and the weight, it is assumed that it represents a marginal percentage of the total weight and volume of an electric vehicle. It is also worth mentioning that single core copper wires and classical magnetic steel can be used in place of very costly Litz wire and expensive ferrites, which is of great interest for a strategy aimed at increasing the market penetration. Considering all the above potential changes, it is obvious that a lower frequency drastically reduces the overall cost of the wireless solution. However, the overall efficiency of the system is quite similar to higher frequency systems and can reach values around 80% [13]. The remainder of this paper is structured as follows: In Section 2, we present the WPT system under study. The impacts of switching and fundamental switching on the efficiency of the power electronic converter are explained in Section 3. The magnetic components are detailed in Section 5. Then, selected simulation and experimental results are presented in Sections 4 and 6, respectively. Finally, Section 7 draws the conclusion.

2. WPT system description

The WPT system we considered, as shown in Fig. 1, is composed of a rectifier (AC–DC converter) that converts the AC 50 Hz voltage from the grid into a DC voltage. Subsequently, an inverter converts the rectified voltage into a 400 Hz voltage, which is then applied to the transmitter pad (self-inductance L_1 and Resistance R_1) in series with the capacitor C_1 to establish resonance. On the EV side, the receiver pad (self-inductance L_2 and Resistance R_2) is connected in series with the capacitor C_2 which is the input of a rectifier for charging the battery.

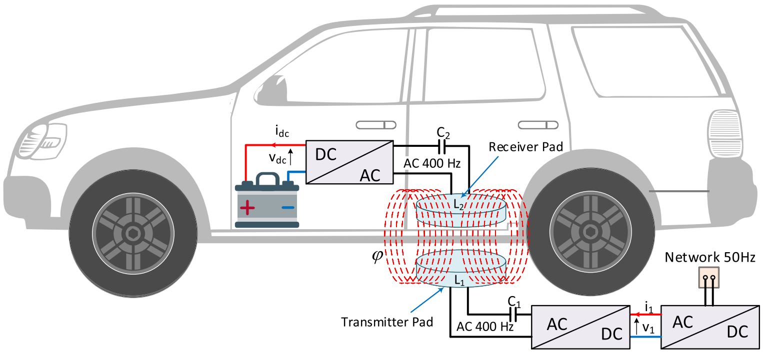


Fig. 1. Schematic of the studied WPT system. On can see the entire energy conversion chain, *i.e.* from the grid to the battery of the vehicle.

3. Power electronics converters efficiency

Power losses in power semiconductor switches can be broadly divided into two categories: (1) static losses and (2) dynamic losses. Static losses consist of on-state power losses or conduction losses, as well as off-state losses. However, off-state losses are usually neglected because leakage current is typically negligible. Dynamic losses, on the other hand, consist of turn-on and turn-off losses, which then drastically depend on the switching frequencies, so it is worth reducing it. The most critical losses to be considered in IGBTs and SiC MOSFETs converters are the conduction losses and the switching losses. In [14,15], the performances of power inverters made with IGBTs and SiC MOSFETs are studied and compared in terms of switching and fundamental frequencies. Based on the results presented in [14], which are shown in Fig. 2, and where the efficiency of both inverters clearly increases with lower switching frequency. It is clear that the SiC MOSFET inverter has better efficiency for these types of applications, especially in a WPT system with a high fundamental frequency, *i.e.* several kHz, where a far higher switching frequency is needed. Therefore, when we reduce the frequency of the WPT system, it is possible to reduce the switching frequency and thus increase the efficiency of the whole system. It is important to mention that the differences in terms of efficiency between both types of switches are reduced for a fundamental frequency of $f_0 = 400$ Hz, which leads us to choose IGBTs as they offer a far less expensive solution. Also, it is assumed that the loss of efficiency of the magnetic part at low frequency can be compensated by the higher efficiency of the power converters.

4. Simulation

To get an idea of the system we needed to build and to design the proposed WPT system, several simulations were performed using the MATLAB Simulink® environment. It is important to mention that we used a full wave inverter for these simulations. This type of converter does not allow the reduction of harmonics or the improvement of power factor, requirements that were deemed unnecessary at this preliminary stage. It is essential to mention that the converters used for these simulations were designed with IGBTs to mirror the configuration used in our experiments. Figure 3 shows simulation results including the emitter voltage V_p and emitter current I_p, load voltage (V_L) and load current I_L. It is worth mentioning that capacitor voltages (V_{C1} and V_{C2}) on both sides of the system nearly reached 1000 V, which represents a constraint for a series resonant system (V_{C1}). Such high voltages also impose

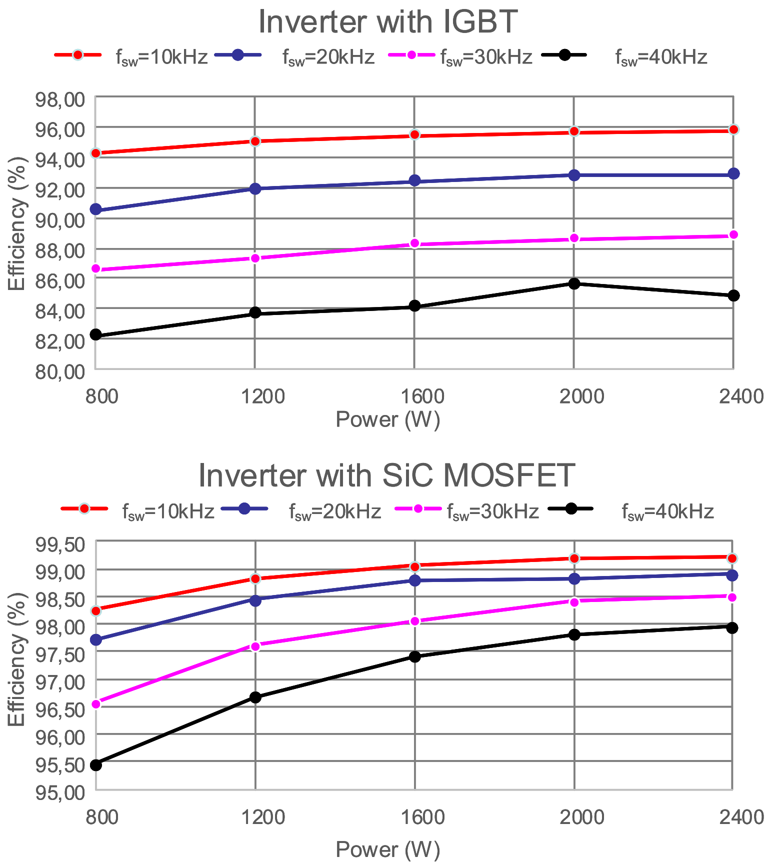


Fig. 2. Total loss comparison in different switching frequencies for an inverter with IGBTs (Top) and an inverter with SiC MOSFETs (Bottom).

limitations on the capacitors of our first prototype test bench and should be seriously considered for future designs. The system parameters are summarized in Table 1. The simulation results depicted in Fig. 3 will serve as a benchmark for the experiments presented below. It is also important to specify that, according to the simulation results, the power supplied from the source to the transmitter side can reach up to 10 kW, while the receivied power on the load side is 8.3 kW. Therefore the achieved global efficiency is around 83% for the whole conversion chain, which represents a realistic power considering EVs charging. However, it is crucial to acknowledge that this power cannot be reached experimentally due to the aforementionned capacitors voltage limitation. In fact, in this case, the voltage across the capacitors would be up to 6000 V, which is far higher than their rated voltage (1000 V). Such constraints will be integrated into the optimization loop of our future work.

5. Magnetic transfer system

To facilitate experiments with different magnetic coupling configurations, and to be compatible with our test equipment, the requirement of the WPT system we needed to build have been determined using the aforementioned MATLAB Simulink® simulations. According to the simulation parameters, the system

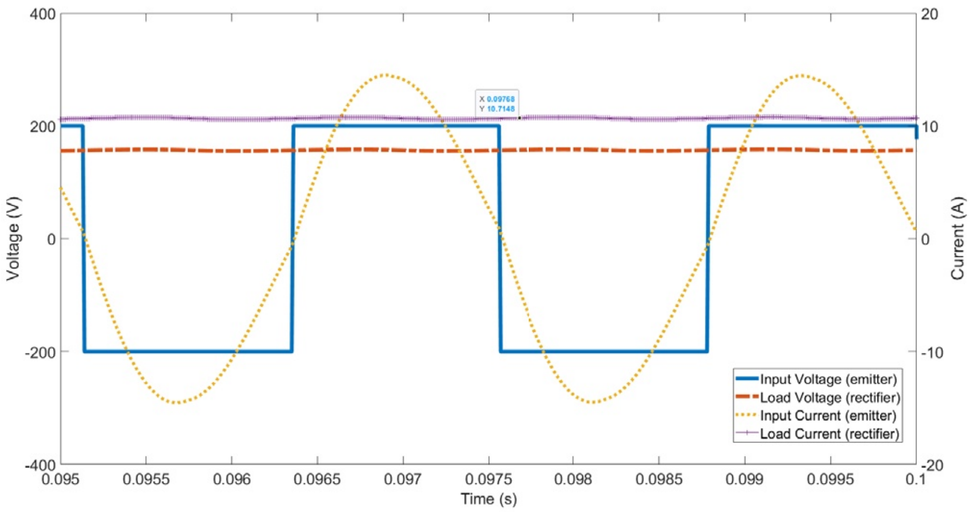


Fig. 3. Simulation results for the IPT system we built. The Input power is 2,085 W and the output power is 1,685 W, which means that the overall efficiency of the system is slightly higher than 80%.

Table 1
WPT System parameters used for simulation and for experimentation
(15 cm air gap)

Element	Value
$L_1 = L_2$	21.72 mH
$C_1 = C_2$	6.8 μF
M	5.65 mH
V_{in}	226 V
f	400 Hz

needs to be composed of two coils of 22 mH with a magnetic coupling coefficient of 0.18 to transmit power up to 8 kW. Compared to high frequency WPT systems [13], the inductance values are considerably higher to reduce the capacitance, *i.e.* tens of mH compared to tens of μH.

As explained before, the system is based on two coupled coils made of 6 mm^2 standard single core copper wires that are far more cost-effective than Litz wires. Additionally, ferrite plates are utilized to enhance the magnetic coupling, as depicted in Fig. 4. However, in the future, these ferrites will be changed to standard magnetic steel to reduce costs. Each layer of both the transmitter and the receiver is made of 27 turns, and the overall dimensions of the coils are fully compatible with in-vehicle installation considering an external diameter of 500 mm.

However, as described in Table 2, our WPT device has been designed to offer several degrees of freedom, *i.e.* the distance between the coils can be adjusted with an airgap ranging from 50 to 300 mm, which corresponds to typical ground clearance of various types of cars. Moreover, the number of layers in the primary and in the secondary coils can be selected independently from 1 to 7. This flexibility allows us to adapt the configuration for future work where the transmitter and receiver coils could be slightly different. The Table 2 summarized the main parameters of the proposed IPT system. Due to its relatively

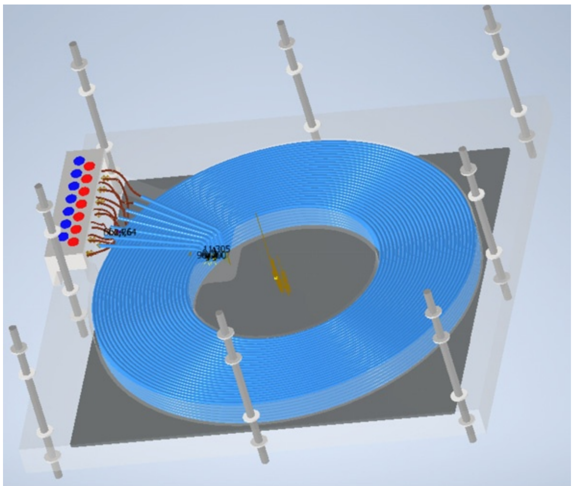


Fig. 4. Picture of half a system (primary and secondary coils are exactly the same). The ferrite plates can be seen under the coil. For information, the outer diameter of the coil is 500 mm, the internal diameter is 250 mm, and the air gap can be adjusted from 50 to 300 mm.

Table 2
Geometric parameters of our system and corresponding magnetic and electrical quantities

Parameters		
Nc_1	1 to 7	Number of layers of coil #1
Nc_2	1 to 7	Number of layers of coil #2
e	50 to 300 mm	Distance between coils
D_{int}	250 mm	Inner diameter of coils
D_{ext}	500 mm	Outer diameter of coils
Corresponding magnetic quantities		
L_1	0.7 to 23.82 mH	Self-inductance of coil #1
L_2	0.7 to 23.82 mH	Self-inductance of coil #2
R_1	103 to 720 mΩ	Resistance of coil #1
R_2	103 to 720 mΩ	Resistance of coil #2
M	0.053 to 14.21 mH	Mutual inductance
k	0.1 to 0.737	Magnetic coupling coefficient

simple geometry, the magnetic field, the flux accross the coils, and subsequently the self and mutual inductances can be computed using the Finite Element Method applied to a 2D axisymetric problem by assuming the ferrite plates are circular. In this paper, we used the open-source FEMM [16] software to evaluate the self inductances L_1 and L_2, and the mutual inductance M, as shown in Fig. 5. Then, the coupling coefficient between the emitter and receiver pads was determined, as depicted in Fig. 6. It is important to note that, for the sake of clarity, the presented results consider the same number of turns for each coil (series connected layers), i.e. $Nc_1 = Nc_2$. However, it is nevertheless possible to calculate L_1, L_2, M and k for all available configurations. Based on these parameters, we built the IPT system

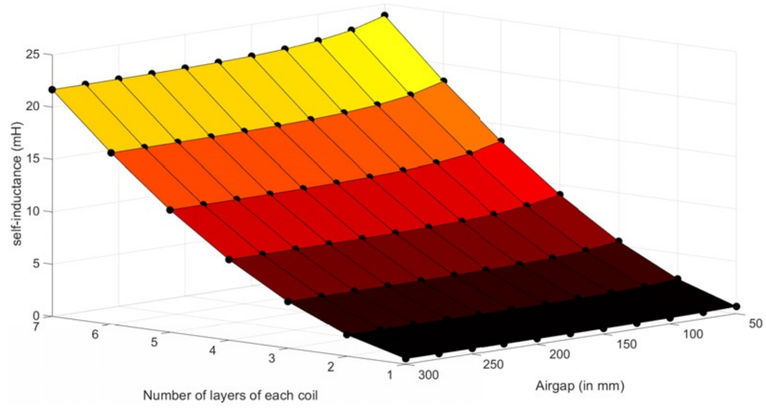


Fig. 5. Example of the evaluation of the self-inductance L_1 and L_2 (primary and secondary coils are exactly the same). Please note that the presented results consider the same number of turns for each coil (series connected layers), *i.e.* $Nc_1 = Nc_2$.

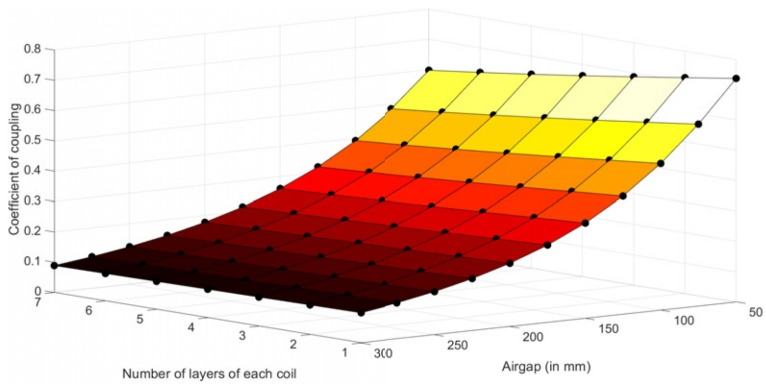


Fig. 6. Example of the evaluation of the coefficient of coupling k. Please note that the presented results consider the same number of turns for each coil (series connected layers), *i.e.* $Nc_1 = Nc_2$.

depicted in Fig. 7. Measurements carried-out on the experimental setup indicate that the relative deviation of the self inductance values of each layer is under 5% between FEM calculations and measurements. As shown in Table 3 and Table 4, experimental and numerical results are very close for all the magnetic characteristics of the system, including mutual inductance estimation, which are all key parameters for accurate simulations and system design.

6. Experimental test results

The experimental setup can be observed in Fig. 7. It consists of various components, each of which is described below. The primary power source is an IGBTs-based full-wave inverter (Semikron SKM150GB12T4) powered by an isolated DC source (TDK-Lambda GPS600-25.5 0-600V/0-25.5 A). The inverter allows for adjustable frequency and both the inverter and the source have the potential for power scaling in future work. The full-wave inverter is ideal for this first step, as it simplifies the system, while allowing us to carry out power measurements and offering the possibility of switching to

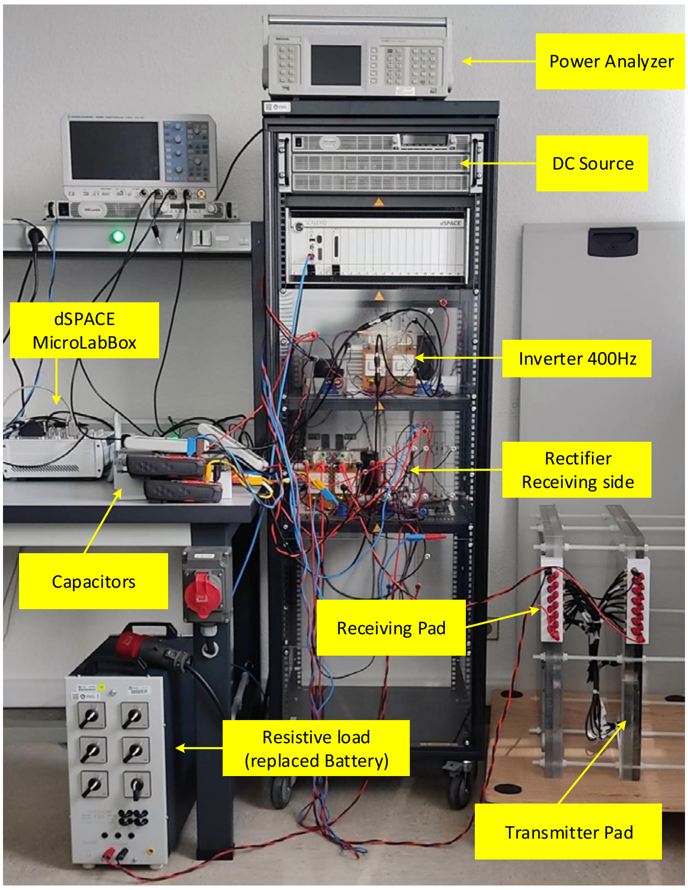


Fig. 7. Experimental test bench of the IPT system.

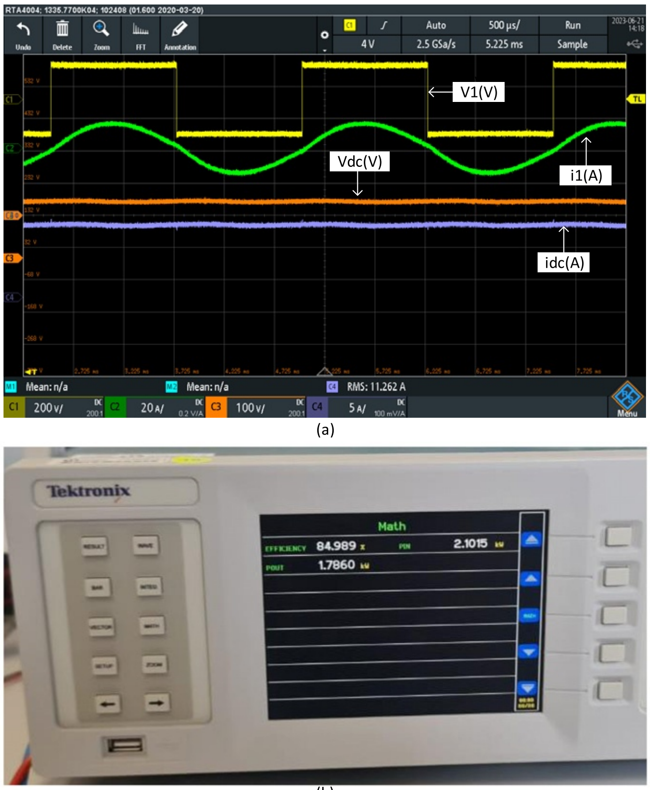
Table 3
Comparison of the calculated and real values of the self inductances of the different layers of each coil. The further the layer is far from ferrites, the lower is the value

Location	Calculated value (μH)	Measured value (μH)
1	539	560
2	515	534
3	496	512
4	478	491
5	462	481
6	461	450
7	449	438

PWM control. The coils and capacitor banks are designed to be modular, enabling their usage at different operating points. Capacitor values were carefully chosen and combined in series and/or parallel to tune the resonant frequency and achieve the desired capacitor value (C_1 and C_2). The rectifier connected to

Table 4
Magnetic characteristics of the 7/7 layer configuration with a spacing of 25 cm. Values of inductances indicated in mH

Parameters	FEM	Measured
L_1	21.72	22.24
L_2	21.72	22.1
M	3.86	4.0
k	0.178	0.184



(a)

(b)

Fig. 8. Experimental results (a) Input 400 Hz voltage and current (v_1, i_1) and output dc side voltage and current (v_{dc} and i_{dc}) (b) the input and output power measured by the power analyzer.

the receiving coils is composed of two SKM100GB12T4 modules and, as no commands were sent to the transistors, it worked as a full-wave diode rectifier. However, it is worth mentioning that we have the opportunity to control the rectifier, which will enable us to optimize the system in future work (MPPT). To control the whole system, a dSPACE MicroLabBox was employed. The primary and secondary voltages and currents were measured and sent to the dSPACE system for real-time monitoring and control of the system's performance. A power analyzer (Tektronix AP4000) was used to measure the output, *i.e.* at load terminals and input power of the system, which is the output of the DC Source in our setup. Figure 8 presents the results of an experimental test. In Fig. 8(a), the output voltage of the inverter (v_1) and the primary side (transmitter side) current (i_1) can be observed, along with the output voltage and current after the rectifier on the receiving side (v_{dc} and i_{dc}). Figure 8(b) displays the input and output power measured by the power analyzer. The results indicate that the input power is 2,101 W and the output power is 1,786 W, resulting in an efficiency of 85 % for the system. The experimental measurements show very good agreement with the numerical simulation results, which is very encouraging for this first step toward low frequency wireless power transfer. This also shows that the overall efficiency of the complete system is high, even if no optimization has been carried out yet.

7. Conclusion

This paper presents the first step toward IPT-based systems operating at very low frequencies, *i.e.* a few hundred Hz compared to tens of kHz, which is of a great interest for safety, system integration and cost reduction, particularly with the possibility of using much less expensive materials and converters. It is worth mentioning that this first step of the system has not been optimized so far, and further improvements are expected in future developments. However, very interesting observations can be made from this preliminary work. Indeed, simulations and experimental results show that the lower efficiency of the IPT can be partially compensated by the better efficiencies of the power electronic converters, and the efficiency can reach up to 80% considering grid to battery transfer at frequencies as low as 400 Hz.

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References

[1] M.T. Tran, S. Thekkan, H. Polat, D.-D. Tran, M. El Baghdadi and O. Hegazy, Inductive wireless power transfer systems for low-voltage and high-current electric mobility applications: Review and design example, *Energies* **16**(7) (2023), 2953.

[2] Y. Zhang, Y. Wu, Z. Shen, W. Pan, H. Wang, J. Dong et al., Integration of onboard charger and wireless charging system for electric vehicles with shared coupler, compensation, and rectifier, *IEEE Transactions on Industrial Electronics* **70**(7) (2023), 7511–7514.

[3] Y. Zhang, S. Chen, X. Li and Y. Tang, Design of high-power static wireless power transfer via magnetic induction: An overview, *CPSS Transactions on Power Electronics and Applications* **6**(4) (2021), 281–297.

[4] H.T. Nguyen, J.Y. Alsawalhi, K. Al Hosani, A.S. Al-Sumaiti, K.A. Al Jaafari, Y.-J. Byon et al., Review map of comparative designs for wireless high-power transfer systems in EV applications: Maximum efficiency, ZPA, and CC/CV modes at fixed resonance frequency independent from coupling coefficient, *IEEE Transactions on Power Electronics* **37**(4) (2022), 4857–4876.

[5] J.K. Nama and A.K. Verma, An efficient wireless charger for electric vehicle battery charging, in: *2020 IEEE 9th Power India International Conference (PIICON)*, 2020, pp. 1–5.

[6] Y. Li, S. Liu, X. Zhu, J. Hu, M. Zhang, R. Mai et al., Extension of ZVS region of series–series wpt systems by an auxiliary variable inductor for improving efficiency, *IEEE Transactions on Power Electronics* **36**(7) (2021), 7513–7525.

[7] S. Kim, M. Amirpour, T. Dharmakeerthi, V.Z. Barsari, G. Covic, S. Bickerton et al., Thermal evaluation of an inductive power transfer pad for charging electric vehicles, *IEEE Transactions on Industrial Electronics* **69**(1) (2022), 314–322.

[8] S.Y. Jeong, V.X. Thai, J.H. Park and C.T. Rim, Self-inductance-based metal object detection with mistuned resonant circuits and nullifying induced voltage for wireless EV chargers, *IEEE Transactions on Power Electronics* **34**(1) (2019), 748–758.

[9] Y. Wang, J. Mai, Y. Yao and D. Xu, Analysis and design of an IPT system based on S/SP compensation with improved output voltage regulation, *IEEE Transactions on Industrial Informatics* **16**(5) (2020), 3256–3266.

[10] Y. Zhang, S. Chen, X. Li and Y. Tang, Design methodology of free-positioning nonoverlapping wireless charging for consumer electronics based on antiparallel windings, *IEEE Transactions on Industrial Electronics* **69**(1) (2022), 825–834.
[11] A. Ahmad, M.S. Alam and R. Chabaan, A comprehensive review of wireless charging technologies for electric vehicles, *IEEE Transactions on Transportation Electrification* **4**(1) (2018), 38–63.
[12] S.A.Q. Mohammed and J.-W. Jung, A comprehensive state-of-the-art review of wired/wireless charging technologies for battery electric vehicles: Classification/common topologies/future research issues, *IEEE Access* **9** (2021), 19572–19585.
[13] G. Buja, M. Bertoluzzo and K. Naik Mude, Design and experimentation of WPT charger for electric city car, *IEEE Transactions on Industrial Electronics* **62**(12) (2015), 7436–7447.
[14] P. Poolphaka, E. Jamshidpour, N. Takorabet and T. Lubin, Performance comparison between IGBT and SiC devices in three-phase inverter for high-speed motor drive applications, in: *2022 25th International Conference on Electrical Machines and Systems (ICEMS)*, 2022, pp. 1–6.
[15] P. Poolphaka, E. Jamshidpour, T. Lubin, L. Baghli and N. Takorabet, Comparative study of IGBT and SiC MOSFET three-phase inverter: Impact of parasitic capacitance on the output voltage distortion, *Actuators* **12** (2023), 355.
[16] D.C. Meeker, *Finite Element Method Magnetics, Version 4.2*.