

An Integrated Approach for Dynamic Charging of Electric Vehicles by Wireless Power Transfer - Lessons Learned from Real-Life Implementation

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ABSTRACT

The aim of this paper is to introduce a complete fast dynamic inductive charging infrastructure from the back-office system (EV management system) up to the Electric Vehicle (EV) (inductive power transfer module, positioning mechanism, electric vehicle modifications) and the EV user (User interface). Moreover, in order to assess the impact of the additional demand of inductive charging on the grid operation, an estimation of the 24-hour power profile of dynamic inductive charging is presented considering, apart from the road traffic, the probability of the need for fast charging, as well as the specifications of the proposed solution. In addition, an energy management system is presented enabling the management of the operation of the inductive charging infrastructure, the interaction with the EV users and the provision of demand response services to different stakeholders. The proposed dynamic inductive charging approach has been demonstrated within a real urban environment in order to provide useful insights regarding the experience gained from a real-field trial. The relevant practical conclusions are also discussed in this paper. Finally, a cost/benefit analysis, according to the Discounted Cash Flow (DCF) principles, is performed in order to assess the economic viability of the proposed solution.

CITATION: Karakitsios, I., Karfopoulos, E., Madjarov, N., Bustillo, A. et al., "An Integrated Approach for Dynamic Charging of Electric Vehicles by Wireless Power Transfer - Lessons Learned from Real-Life Implementation," *SAE Int. J. Alt. Power*, 6(1):2017, doi:10.4271/2017-01-9076.

INTRODUCTION

Fast inductive charging, can dramatically change the “usability” and attractiveness of electric vehicles to consumers by improving both the charging duration and the convenience offered. Even though wireless charging technology is rather premature, there are already some commercially available solutions enabling slow charging (i.e. 3.3kW) which are compatible with specific car models (e.g. Nissan, Siemens, Bosch/Evatran [1] etc).

The operational principle of the Inductive Power Transfer Module (IPTM) resembles to the one of transformers; transferring energy from a primary to a secondary coil (usually referred to as “pick-up coil”) which are not physically connected as it is presented in [2]. In the majority of the IPTM designs proposed in the literature [3]-[12], ferrite is usually implemented for reinforcing the magnetic flux. The experience from the early IPTM design of double sided couplers introduced in [3]-[4] indicated that the magnetic losses are increased and suppression issues of the field leakage are raised [5]. In order to overcome such issues, new IPTM topologies were proposed with circular coils placed above a ferrite layer or embedded in it, using a circular arrangement [6]-[7]. The main disadvantages of such

topologies are the very limited power transfer rate in case of a large air gap and their quite low tolerance concerning the horizontal misalignment. The Double-D or DD pad introduced in [5], [8], enables the transfer of a greater amount of power compared to circular pads, while the DDQ pad and the bipolar pad [8]-[9], further increase the tolerance to misalignment.

Concerning dynamic inductive charging, two main design approaches exist. In the first one, the primary coil comprises a long coil going across a long ferrite track, while the secondary coil is much smaller. The design is characterized by the shape of the track it comprises, leading to the E, U or W-type coupler [10], or the newly introduced I-type coupler [11]-[12]. In the second design approach, the on-route inductive charging system comprises several successively placed “segments” [5] similar to the ones used in static inductive charging. The operation of each pad may be managed by separate power electronic interfaces increasing, thus, considerably the cost of such solution. In this respect, new control techniques have been proposed in the literature enabling the management of two or more pads by the same power electronic interface [13]-[14].

In order to provide a high frequency current to the primary coil, the AC power provided from the grid is converted to a DC power source which is then converted to a high frequency current through a DC/AC converter. The alternating magnetic field induces an AC voltage on the receiving coil, which is finally rectified to provide a DC voltage to the battery of the EV. Many control schemes have been proposed either limited to the primary [15]-[17] or the secondary side [18]-[20], or applied to both sides of the IPT system [21]-[22]. In order to reduce the re-active power losses in the primary side and ensure a high output power and efficiency a compensation network is incorporated in the design. Depending on the way the capacitors are connected to the primary and secondary coils four basic topologies may exist: series-series (SS), series-parallel (SP), parallel-parallel (PP), parallel-series (PS) [2]. More complex methods for the compensation network have also been proposed in order to improve the tolerance to misalignment [23]-[24]. Variable tuning also appears as a compensation solution, allowing the control of the capacitance or inductance values [25]-[26].

The power transfer rate of an IPTM is subject to the relative positioning (i.e. vertical and horizontal misalignment) of the primary and secondary coils. Several approaches have been introduced aiming to achieve the optimal positioning of the Electric Vehicle and attain the maximum transfer power rate. The Unplugged project suggested a complicated positioning methodology of the vehicle with respect to an RFID system, a camera and the vehicle’s odometry data [27]. The Primove project suggests a lifting and lowering mechanism which is only applicable for buses. Furthermore, there are several patents [28]-[31] related to the positioning system which, however, allow for limited lateral displacement and comprise heavy materials and components requiring large space of the EV. The positioning mechanism that was developed and is introduced in this paper, is a fully functional system designed for commercial vehicles, enabling the continuous charging of the EV at high power transfer rate considering a realistic air gap between the coils.

Besides the social benefits, the integration of fast inductive chargers into power systems raises new grid operational challenges to the system operators. The nominal installed capacity of a fast inductive charger can be high enough (>30kW) resulting in a significant network load profile modification. The energy needs of dynamic inductive charging stations have been studied in [32]-[33], considering the traffic on the roads and based on theoretical scenarios regarding the operational characteristics of the stations, while a general scheme for the provision of real-time V2G services by dynamic inductive chargers is examined in [34]-[35]. In this paper, the power profile of dynamic inductive charging is estimated, considering parameters not just limited to road traffic, but also the probability of the need for fast charging, as well as the specifications of the proposed solution. An energy management system is also designed and developed in order to offer demand response services to the market operator in case of network operational issues arising due to the increased demand of the dynamic inductive charging stations.

The main contribution of the paper lies in the following aspects:

- It introduces a complete dynamic inductive charging system (IPTM design, IPTM control, positioning mechanism, energy management system)
- It provides an estimation of the additional charging demand which is expected to affect network operation.
- A cost/benefit analysis, according to the Discounted Cash Flow (DCF) principles, is performed in order to assess the economic viability of the proposed fast dynamic inductive charging solution.

The rest of the paper is organized as follows: The overall architecture and the specifications of each module of the proposed dynamic inductive charging system are presented in [Section II](#). The proposed dynamic infrastructure is demonstrated in real urban environment and the results are discussed in [Section III](#). Furthermore, the simulation tool and the results from the demand profile analysis of a dynamic inductive charging network are analysed in [Section IV](#). Moreover, the conclusions of the Cost/Benefit analysis are presented in [Section V](#). Finally, the paper concludes in [Section VI](#).

PROPOSED FAST INDUCTIVE CHARGING CONCEPT

Overall System Architecture

The main objective of the proposed fast dynamic inductive charging solution is to foster the democratization of EVs within the urban environment by developing a comfortable and easily implemented charging solution. Such a solution is expected to promote the use of EVs by the large public, while also facilitating their implementation in the urban grid.

The overall system architecture of the proposed fast inductive charging approach with the different modules and their interactions is illustrated in [Figure 1](#). The black lines indicate the energy flow, while

the information exchange is indicated by the red ones. The red line boxes indicate the services offered by the proposed dynamic wireless charging system.

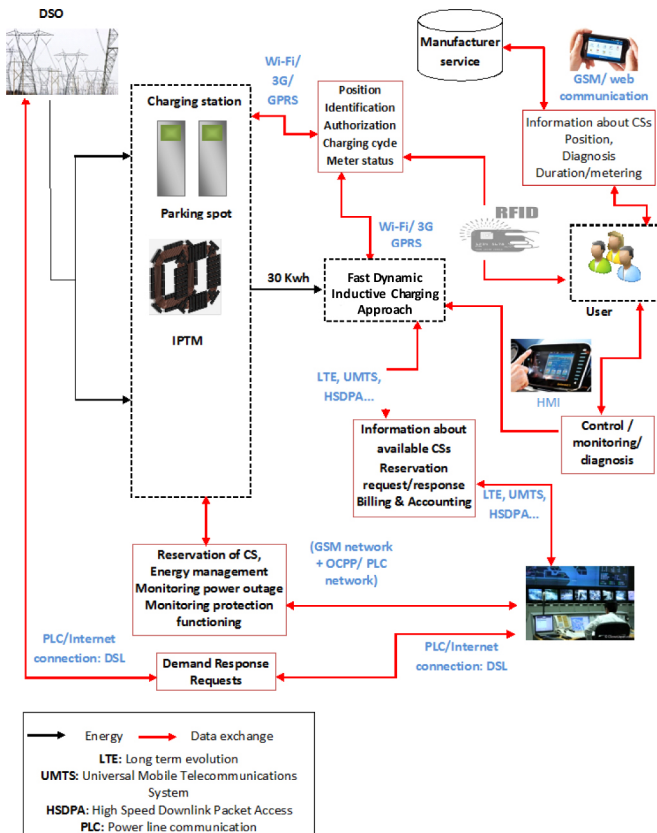


Figure 1. Overall view of the components and interfaces in the proposed fast dynamic inductive charging solution (Source: FastInCharge project)

IPT Module

The proposed dynamic inductive charging station, which is presented in [Figure 2](#), comprises four successively placed primary coils. The power electronics topology consists of a common IGBT module and four IGBT modules, each one connected to one of the four primary coils ([Figure 3](#) - [36]). The common IGBT module is continuously enabled given that the charging station is in operation. Concerning the other four modules, they are enabled successively such that only one module operates each time forming a full bridge converter with the common module ([Figure 3](#)). In order to ensure the activation of one primary coil at a time, magnetic sensors are placed before each primary coil which are activated as the EV passes over them. In order to reduce the voltage applied in the primary coils and assure their galvanic isolation, the converter is connected to each one of the charging coils with a set of two parallel connected transformers TR3||TR4... TR9||TR10. Moreover, a series-series compensation scheme is applied to the design (CS3-CS4...CS9-CS10 for each one of the four primary coils). In order to reduce the high voltage across the compensation capacitors, a set of two capacitors (Csec1-Csec2 for the secondary coil) is used.

The frequency shift control method [36] is adopted in the inverter allowing the control of the output parameters of the IPTM (voltage, current and power supplied to the battery) according to the air-gap

and misalignment between the primary and the secondary coil. In order to efficiently allow greater variations in the high frequency voltage supplied by the converter, the phase shift PWM technique [36] is also incorporated in the design.

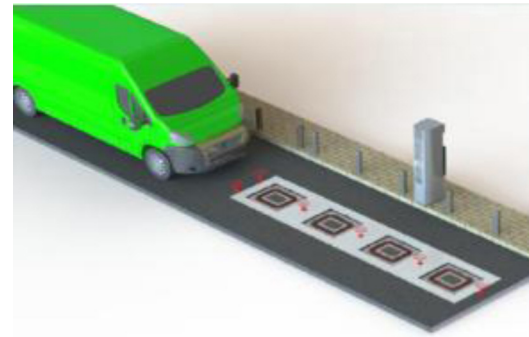


Figure 2. Fast dynamic inductive charging approach (Source: FastInCharge project)

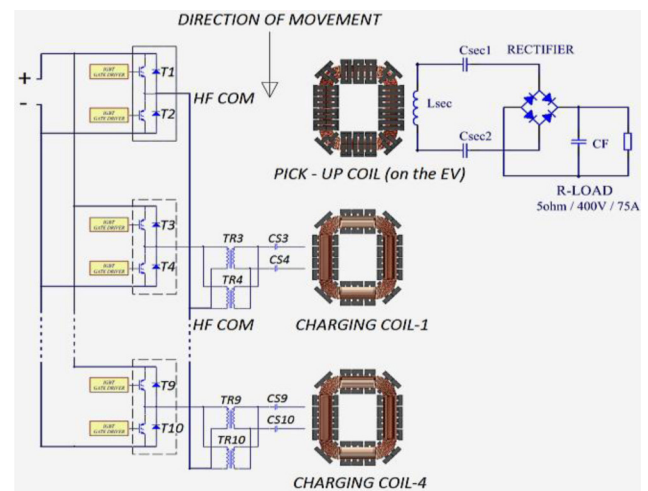


Figure 3. Power electronics topology of the inductive charging station

The IPT module is illustrated in [Figure 4](#). Ferrite is adopted in the coil design in order to enhance and guide the magnetic flux. More specifically, MnZn ferrite plates are implemented due to their relatively high permeability, their excellent mechanical and electrical properties and the fact that they can be easily combined into many possible shapes. In addition, in order to reduce the increased conduction losses due to the high frequency required for the operation of the IPTM, litz wires are used in the design.

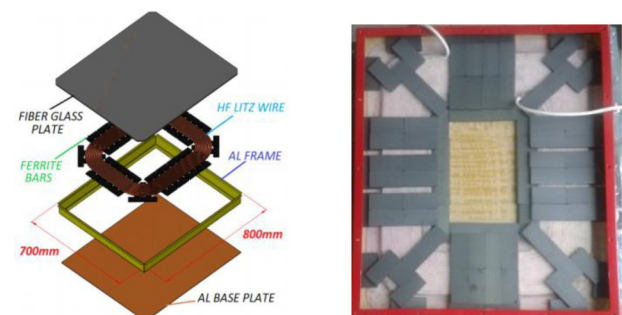


Figure 4. IPTM Coil construction (Source: FastInCharge project)