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# UNPLUGGED Project: Development of a 50 kW inductive electric vehicle battery charge system

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## Abstract

UNPLUGGED project aims to investigate how the use of inductive charging of Electric Vehicles (EV) in urban environments improves the convenience and sustainability of car---based Mobility. In particular, it will be investigated how smart inductive charging infrastructure can facilitate full EV integration in the urban road systems while improving customer acceptance and perceived practicality. As part of the project, two smart inductive charging systems will be built, taking into consideration requirements from OEMs, energy utilities and end users, one of 3,7 kW and other of 50 kW. This paper summarizes the studies carried out in the development of a 50 kW charger for this application, regarding ICPT system, EMI shielding, power electronics and control.

Keywords: *Unplugged project, EV quick charge, inductive power transfer, public transportation, multilevel converters*

## 1 Introduction

The use of electric vehicles (EV) in urban areas presents various advantages, such as no emissions, reduced noise, and lower operational cost when compared to traditional vehicles. One of the main drawbacks for EV, limited range, is not so important in private cars used in cities, since current range in commercially available models can easily cover the distance required by most users.

However, when considering urban public means of transportation, it is not viable to think of providing the vehicle with autonomy to cover its complete route, being necessary to recharge the batteries along the way [1]. This charge process must take little time, ideally the average time required for passengers to go in and out of the vehicle at the stops, and thus, a fast charger must be used.

Charge systems can be classified into two large groups, depending on whether there is electric connection between the vehicle and the charger, or the process is performed inductively. While contact systems are less complex and have a lower cost, inductive solutions present some strong points which make them suitable for this application, such as intrinsic galvanic isolation, absence of mechanical parts, immunity to environmental agents and dust, etc. [2].

This paper describes the process carried out to design a 50 kW inductive charger prototype and summarizes its main characteristics.

## 2 Prototype parameters

The starting point for the development of the charger is knowing the characteristics of the vehicles to be charged, both electrical (e.g. battery voltage) and mechanical (e.g. air gap or maximum coils size). This study considers two different vehicles, trying to make the charger as flexible as possible. The fundamental parameters for the studied vehicles are shown in table 1.

Table 1. Vehicle parameters

| Vehicle 1 | Vehicle 2 |
|---|---|
| **Air gap:** 0.18 to 0.234m | **Air gap:** 0.2 to 0.25m |
| **Selected coil size** 0.3×0.4m | **Selected coil size** 0.3×0.4m |
| **Distance between 25 kW units:** 0.25m | **Distance between 25 kW units**: 0.25m |
| **Battery Voltage:** minimum 259 V, rated 355 V, maximum 380 V | **Battery Voltage:** minimum 700 V, rated 750 V |
| **Maximum misalignment** ±0.1m x-direction and ±0.13 m y-direction. | **Maximum misalignment** ±0.1m x-direction and ±0.13 m y-direction |

In order to be able to supply 50kW at two different voltage levels, a modular system has been developed (fig. 1), composed of two 30kW, 370V chargers, allowing the charge of 355V batteries (vehicle 1) and 700V batteries (vehicle 2) Besides, controlling the primary side it is possible to increase the voltage charge range from 200V to 750V, a very remarkable characteristic regarding interoperability. A scheme of the physical parameters of the coils is shown in fig. 2.

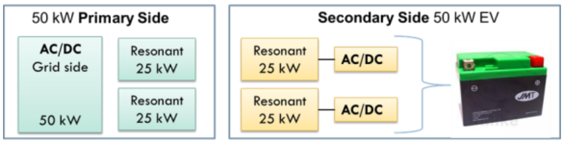


Fig. 1.Block diagram of the modular charger.

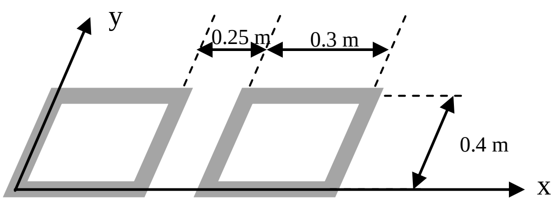


Fig. 2. Schematic coil diagram.

Among the different possible compensation topologies for the inductively coupled power transfer system (ICPT), SP-S has been selected (fig. 3), since it acts as a current source, which is suitable for battery charge and, besides, it shows a very stable and controllable behavior when charge conditions differ from their rated values (position, distance, battery voltage,…) [3].

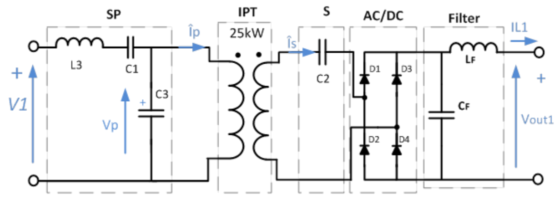


Fig. 3. Scheme of the SP-S ICPT system

Fig. 4 shows the operation ranges of the system. Depending on the voltage of the storage system to be charged, a serial or parallel connection of the modules will be performed. It can be noticed that, although the system is designed to be able to supply 60 kW, a 50 kW limit has been implemented, in order to prevent overloading the batteries of the vehicle.

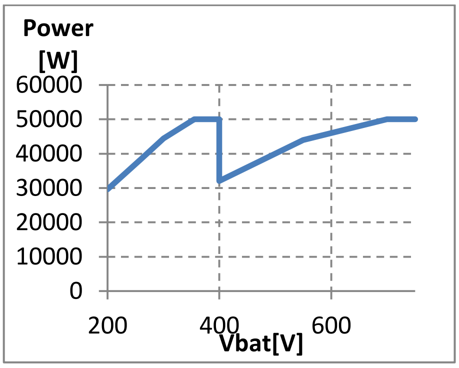


Fig. 4. Maximum power vs. battery voltage.

## 3 EMI shielding

According to international Standard ICNIRP-2010 (International Commission on Non-Ionizing Radiation Protection) the maximum magnetic field exposure for general public, at a 25 kHz frequency, is 27μT [4]. This makes necessary the use of magnetic shielding in order to reduce the high magnetic field generated by the ICPT system.

Shielding is achieved surrounding both coils with a material which has a high conductivity, while having low magnetic permeability, such as copper, aluminum or stainless steel. Considering the results obtained using finite elements programs, aluminum has been selected, since it is lighter and has a lower cost. However, if only aluminum is used, power transfer capacity is significantly reduced, making it impossible to transfer the rated 30kW. To compensate this effect it is necessary to include ferrite into the magnetic circuit, trying to keep the mutual inductance coefficient of the shielded system in the same value as in the unshielded one.

Several ferrite and aluminum shape and position combinations have been studied, considering the available space and the position in the vehicle.
The simulated coil is shown in fig. 5, and the complete solution including shielding is represented in fig. 6.

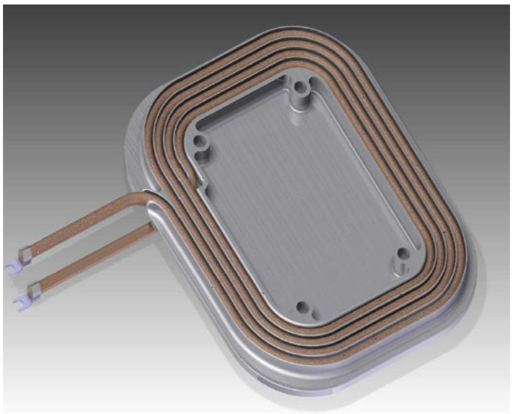

Fig. 5. Implementation of one emitting coil, performed using Solid Works

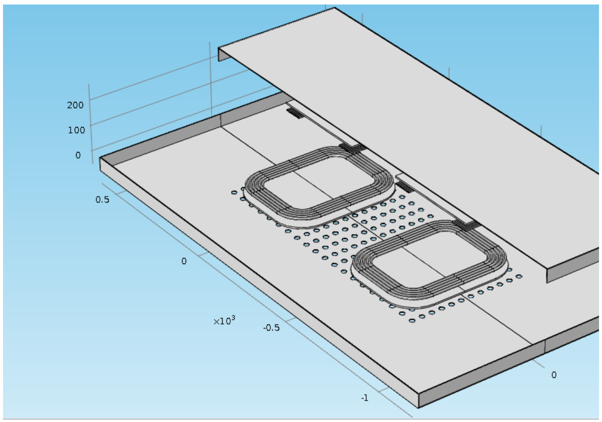


Fig. 6. Configuration of the two 30 kW units, including shielding

The following figures show that the magnetic field is always below the maximum permitted values outside the shielded area, both with coils perfectly aligned (fig. 7) and with maximum misalignment (fig. 8).

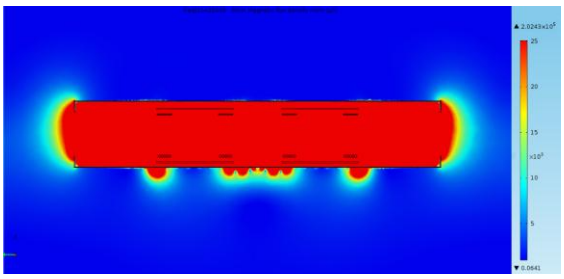

Fig. 7. Shielded system with coils in the centered position and rated air gap

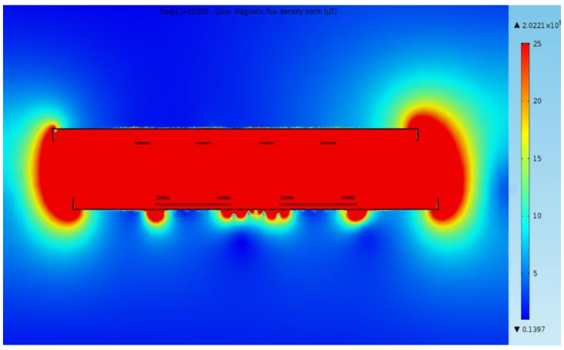

Fig. 8. Shielded system with coils in maximum misaligned position (x = 0.1m, y = 0.13m)

## 4 Power electronics

The power electronic stages required to implement the charger are represented in fig. 9. The system is fed from a 400 V three phase grid, and the first stage is a controlled multilevel rectifier which provides an adjustable DC voltage to the resonant converters. These converters feed the primary coils with a square wave and operate in resonance to reduce switching losses. Power is transferred to the secondary coil and the induced AC voltage is rectified to feed the batteries.

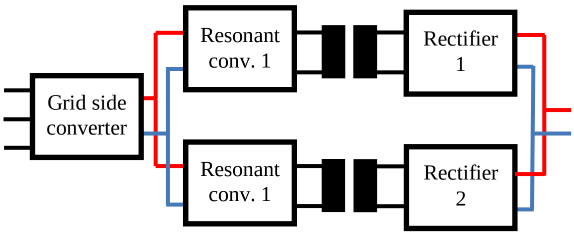


Fig. 9. Block diagram of the power electronic configuration (parallel connection)

### 4.1 Grid side converter

The topology chosen for the grid side rectifier is a NPC three level inverter (fig. 10). Its main advantage compared to a two level inverter is that it uses lower voltage IGBTs (600-650V) for a grid voltage of 400Vac, generating lower losses [5].

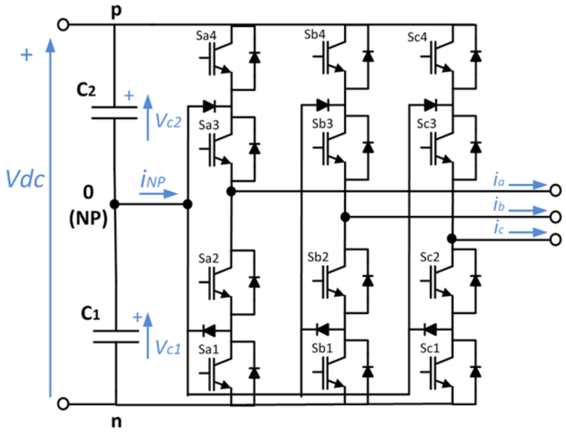


Fig. 10. Schematic of the power electronic stage used in the grid side.

## 4.2 Resonant topology

The energy transference in an induction system of recharge is made by a high frequency alternating magnetic field. Due to the high working frequency (above 25kHz), it is necessary to use resonant converters to reduce switching losses and increase system efficiency [6].

Resonant converters use the resonances of circuit capacitances and inductances to shape the waveform of either the current or the voltage across the switching element, such that when switching takes place, there is no current through or voltage across it, and hence no power dissipation. A Zero Current Switching (ZCS) has been chosen.

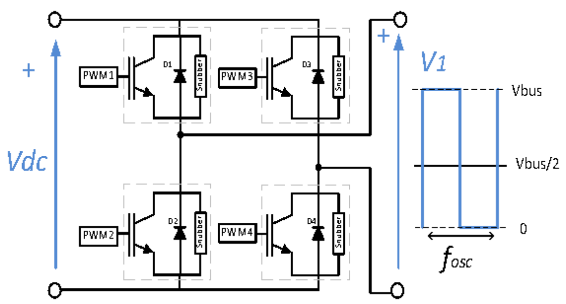


Fig. 11. Scheme of the power stage.

## 4.3 Secondary side

The secondary side is formed by the next components (fig. 12): secondary coil and serial capacitor, diode rectifier bridge, filter and battery. It can be noticed that there is not any controlled component, so the control of the secondary current is performed from the primary side converter.

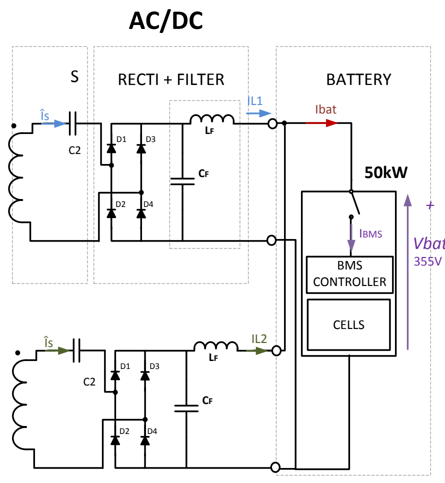


Fig. 12. Secondary side topology.

# 5 System control

In order to assure resonant behavior of the topology, both voltage and frequency of the resonant topology must be controlled, depending on EV battery voltage, coil misalignment and air gap.

## 5.1 Battery voltage variation

Considering battery voltage, the system only operates in resonance this voltage is at its rated value (335V). If voltage is lower, primary current leads primary voltage (fig. 13), increasing switching losses.

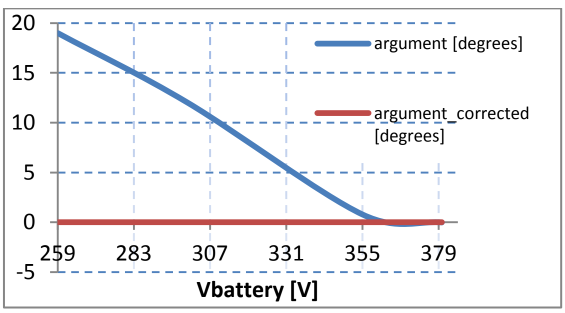


Fig. 13. Primary current displacement with and without control

A suitable control is required in order to operate in resonance, searching a new frequency (fig. 14) and adjusting bus voltage (fig. 15). The maximum correction is required when battery voltage is minimum (259V). In this case bus voltage is kept almost constant and frequency has to be increased in 600Hz (2.4%).

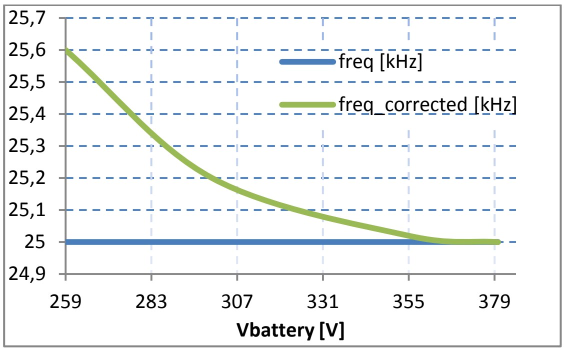


Fig. 14. Frequency correction to operate in resonance (battery voltage variation)

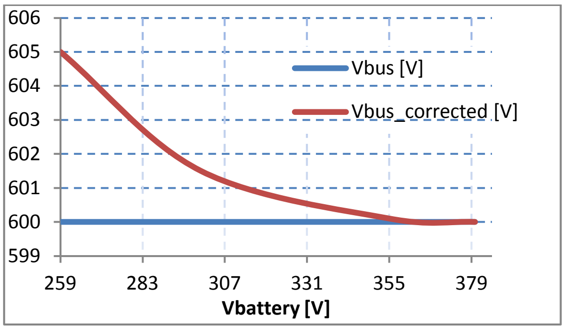


Fig. 15. Voltage correction to operate in resonance (battery voltage variation)

## 5.2 Air gap variation

Considering resonance loss (fig. 16) it can be noticed that if voltage battery is low, current lags for any air gap, while if battery voltage is at its rated value or above it, current leads if air gap is reduced, and lags if it is increased.

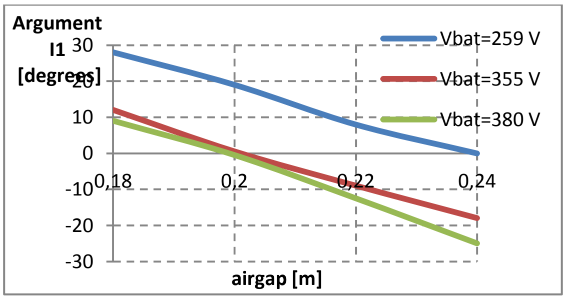


Fig. 16. Argument of I1 vs. air gap for different battery voltages

Frequency must be increased when current leads and reduced when it lags (fig. 17). The higher frequency variation appears when batteries are discharged and air gap is minimum. Bus voltage has to be increased if air gap is below its rated value and reduced in the opposite situation (fig. 18).

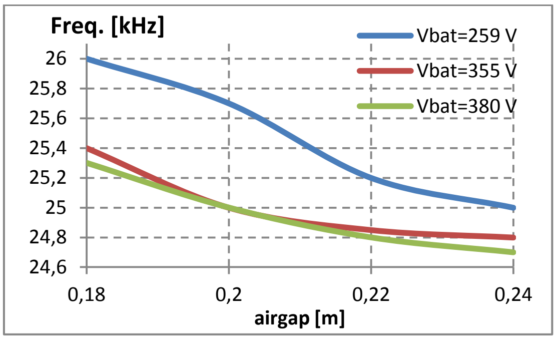


Fig. 17. Frequency correction to operate in resonance (air gap variation)

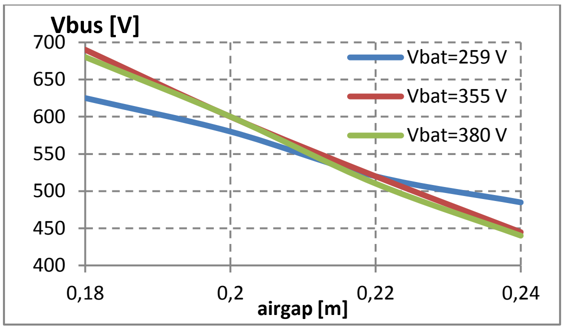


Fig. 18. Voltage correction to operate in resonance (air gap variation)

## 5.3 Misalignment

Required control in this situation is shown in fig. 19 and fig. 20. It consists in decreasing bus voltage to control battery charge current and slightly decreasing operating frequency to find the new resonance.

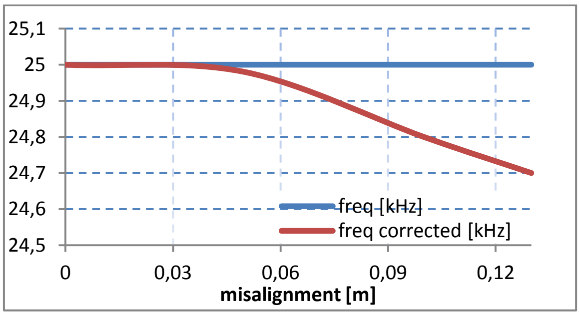


Fig. 19. Frequency correction to operate in resonance (misalignment)

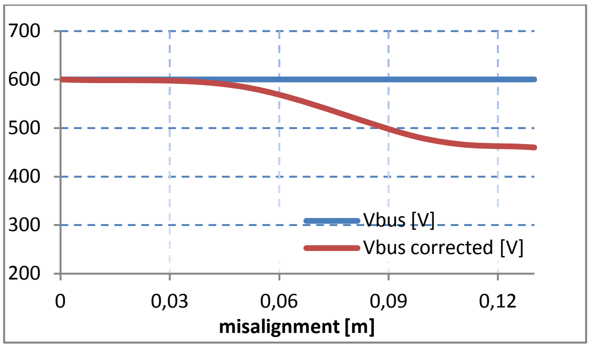


Fig. 20. Voltage correction to operate in resonance (misalignment)

## Recap

The paper presents the results obtained in the development of a 50 kW inductive charger for electric vehicles.

The ICPT configuration chosen is a SP-S system, which has suitable current source characteristics and can be controlled to operate with different charges (i.e. vehicle batteries with different voltage and/or power ratings). Two 30 kW systems have been combined to increase flexibility.

The inductive system has been shielded using a combination of aluminum and ferrite in order to reduce the emitted magnetic field to acceptable values, while keeping the power transfer close to its unshielded value. Finite element simulations have been used to choose a suitable shield configuration.

The power electronic stages used are a multilevel grid rectifier, two resonant converters to feed the primary coils, and two high frequency rectifiers for the secondary windings.

Finally, the corrections in frequency and bus voltage required to compensate for non-ideal operation (variable battery voltage, air gap and misalignment) has been presented, showing that the system is able to operate even under these conditions.

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