DESIGN AND ANALYSIS FOR DYNAMIC WIRELESS CHARGING INFRASTRUCTURE IN INCIT-EV H2020 PROJECT

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ABSTRACT

Expecting future large increase of EVs infrastructure implementation to the distribution network, grid's power quality should be analyzed to ensure best performance. In INCIT-EV European project [1], companies and research laboratories work together to design solutions considering different use case studies, different types of electric vehicles and different charging solutions. This paper focus on the use case of Versailles: Dynamic wireless charging on highways (90 kW power – 80m lane – 130 km/h vehicle speed).

This innovative concept will be tested on the Versailles experimental site by UGE/Vedecom/CIRCE/Enedis.

Keywords: wireless power transfer system, energy storage system, grid impact reduction, D-STATCOM.

INTRODUCTION

As a new growing field of study, many researches have been conducted in the last decade on wireless power transfer systems WPTSs, and since those systems are multidisciplinary, the proposed solutions are widely dispersed, as shown in [2], which makes keeping tracks of all of them almost impossible. Starting from the decision between static [3] or dynamic [6][7] charging, inductive or conductive [8][9], single phase or three phase coils topology [8], to the proposed compensation topology [9] (ss, sp, ps, pp, LC, LCC, LCCC, etc…), to power electronics architecture and their control, to their electromagnetic emission impact on passengers [13] [14], taking into consideration the transmitter and receiver coils (or capacitors) technologies and dimensions [12]. Until present, we could not decide which technology is better in terms of efficiency, profitability, etc…

As a partner of the project, University Gustave Eiffel is conducting researches mainly dedicated to the specific constraints of the use case of Versailles, which concerns high speed EV's recharging (highway) [11]. Besides test lane described in the abstract, study will take into consideration a 25 km wireless power charging lane, with 34 MW maximum power. It is important to differentiate simulations for 90 kW one EV charging from the 34 MW full EVs integration. High dynamic variable load connected to the grid may results in voltage and frequency oscillation and power factor perturbation. Moreover, with the number of EVs rising, and considering the V2G possibility, the load profile is not known enough & difficult to foresee. Therefore, grid impact needs to be analyzed to support decision in actions ahead of connection & operation. In this project, we investigated different techniques to reduce grid impact, such as Flexible AC Transmission Systems (FACTS), energy storage systems (ESSs), load shifting, etc... In this paper, we are presenting a part of those results, concerning only the usage of D-STATCOM for reactive power compensation and voltage regulation. Since the project is in early study stage, experimental data such as load profile are not yet available. Therefore, our strategic approach is to model the whole energy transfer system, starting from the grid, to the battery inside the electric vehicle. We start by modelling the wireless power transfer system, and its components to understand the electric power needs to charge wirelessly an EV. Then a branch of the electric grid is modeled, and connected to several EVs using the power profile established from part one, in order to study the impact of high integration of EVs into the grid. Finally, understanding those impacts will lead to solution propositions to reduce the impact and support the grid. All simulations are made in specialized power system's toolbox of MATLAB SIMULINK.

WIRELESS POWER TRANSFER SYSTEM FOR DYNAMIC ELECTRIC VEHICLES BATTERY CHARGING: USE CASE OF VERSAILLES

The objective for this use case is to study the possibility of high power (90 kW) dynamic wireless charging on highways at a maximum speed of 130 km/h.

High speed means that the contact between the transmitter and receiver coils will last less time, which results in high switching frequency; and with high transferred power limits the range of possible power electronics technologies that can be used.

In addition, high power means high current at a fixed voltage level. So one of the challenges is to induce high current at short time, which will have impact as drop voltage in inductive circuits. Another challenge in this use case is the need of a fixed DC voltage source of 700 V with a maximum of 5V ripple. Finally, it is obvious that receiver side (inside the car) will be the same in different UCs, and then for different power transfer levels.

The complete model of the proposed WPTS is shown in Figure 1. First, a **three-phase rectifier** is used to convert from 400V three-phase AC **grid** level to 700 V DC, then an **LCLC filter** is used to maintain a DC current at the output of the rectifier. The resonant **transmitter receiver** is based on a **DC-to-AC** single-phase full bridge inverter with bipolar modulation at 85 kHz switching frequency, and an **LCC filter** at both ends. Then an **AC-to-DC** single-phase diode rectifier is used, alongside with a controlled **DC-to-DC** converter to charge the EV's **battery**. The solar PV backup system contains 45 **solar panels** of 355Wc, 3 **DC/DC MPPT chargers**, 3 synchronized single-phase DC/AC inverters (**MultiPlus® II**), a **battery pack** of 8 smart batteries 12.8V 160Ah and a battery controller (**BMV**).

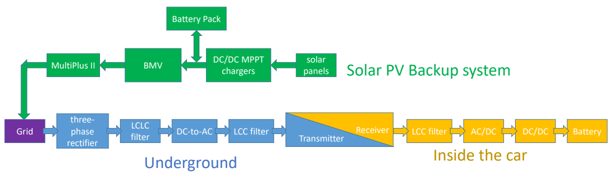

Figure 1: WPTS with backup PV block diagram model

Simulation parameters

The proposed WPTS is an inductive transmitter receiver, with 10m transmitter coil of 17 μH, and 1m receiver coil of 130 μH, with 0.12 coupling coefficient. Several compensation network topologies have been tested during the project, before we settled down with the double-sided LCC filter. The parameters of the WPTS compensation network are calculated based on [13]. The DC voltage level at the exit of the rectifier is 700 V DC with five Volts maximum ripple. The three phase rectifier is a front end converter, based on [14] and [15] with small modifications. A second rectifier model (based on high power three-phase rectifier according to [16], with a passive three phase diode bridge rectifier input filter based on [17]) was also tested during the project. The results for the two models were almost identical expect for total harmonic distortion factor, which was better for the first model. The car is at 130 km/h speed so that the time interval of contact between primary and secondary coils is about 277 ms, and the transmitted power is at 87 kW. We consider a fixed charging current reference for the electric vehicle battery at 207 A, which is equivalent to 87 kW at battery voltage level for the considered SOC of 80%. However, in order to show multiple charging periods, and due to the huge amount of data (maximum sampling frequency is 10 MHz), we are considering the same time of 277 ms as off load time. At 130 km/h, it's equivalent to saying that the distance between two cars is 10m, which is not logical, but since we obtain the steady state of the no load mode within this time, we consider that it's enough for showing the complete results. When in switching between load and no load, and in order to maintain a logical model, we have added an ideal switch that disconnects the load and replace it by an inductance equivalent to the primary inductance of the transmitter.

Simulation results

Figure 2 shows the complete MATLAB model of the system. We can distinguish three parts: the WPTS buried underground with the primary transmitter, the inside-car part including battery pack, secondary receiver and power electronics, and the solar PV Victron® energy system. We can see in Figure 3 the DC voltage and current at the rectifier's output, and the three-phase current absorbed from grid. The grid's current THD is less than 2%, which is important for the next paragraph, when we consider integrating hundreds of EVs model, so we can copy the same voltage and power profile (active and reactive power) and multiply it by the number of considered EVs. The rectifier's efficiency is 99.9% (without considering losses in the IGBTs) and the power factor is at 99.6%.

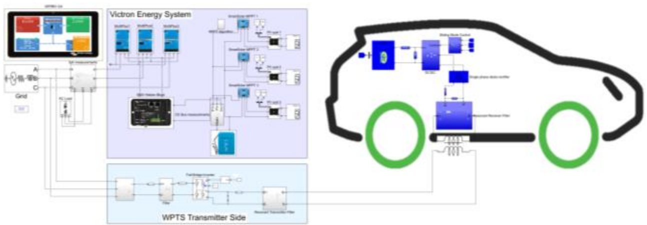

Figure 2: WPTS and PV backup complete model in Matlab Simulink®

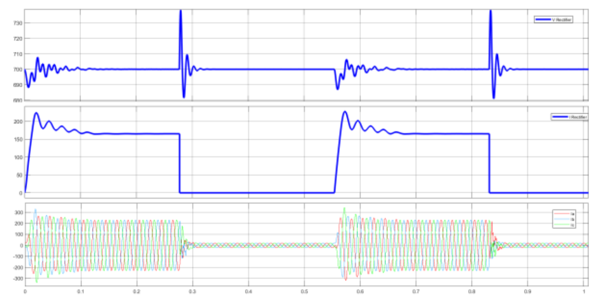

Figure 3: Rectifier's voltage and current outputs, and current inputs for two charging periods

Figure 4 represent the DC current before and after LCLC filter. The filter's parameters are selected to have a minimum current ripple and a fast response time since the charging stage lasts 277 ms. In Figure 5, we are showing the EV's battery parameters: Current, voltage and SOC. The charger is a buck boost converter controlled with the constant current-constant voltage CCCV technique. We can notice two charging periods (or intervals), where the current is controlled at 207 A (CC charging mode).

When the load is disconnected, the current returns to zero with some oscillations. Notice how the SOC is increasing slightly, indicating the charge of the battery. Figure 6 represent the power generated by the solar PV system for different irradiation and temperature values. Voltage control is made here using MPPT algorithm. Notice that expected maximum power (from calculation, in green) and PV measured power (in blue) are almost identical, meaning good functioning of the algorithm. In addition, we can see the efficiency of the converter, which is more than 98% in steady state, except when irradiation is too low.

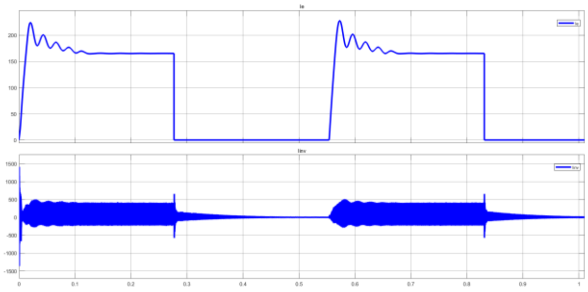

Figure 4: DC current before and after the LCLC filter

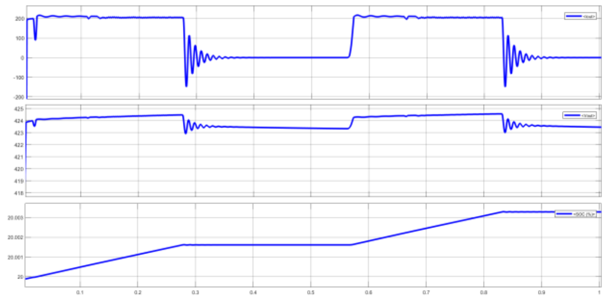

Figure 5: Current, voltage and SOC for the EV's battery

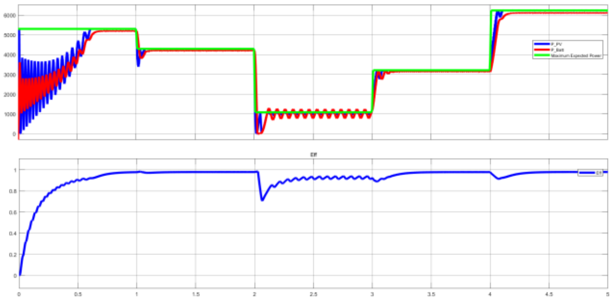

Figure 6: PV power and efficiency

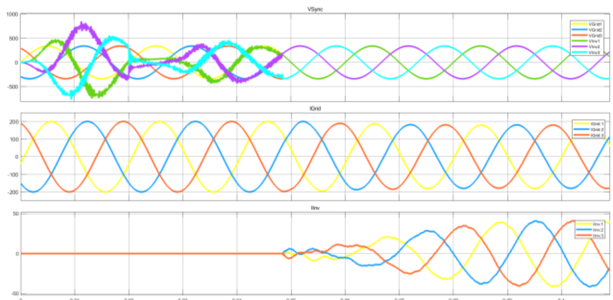

Figure 7: inverter startup: 3 phase voltage and current

Figure 7 represent the synchronization between the three single-phase inverters and the grid. This equivalent to three-phase inverter is commanded to inject controlled active and reactive power to the grid when needed, as a support to the grid.

INTER URBAN GRID MODEL AND IMPACT

Once we understand the power profile needed to charge an EV, the model is generalized to charge EVs connected to the grid. In this session, we will define grid specifications and charging station content. Then simulation data will be analyzed searching for negative impact to the grid.

Proposed model for two charging stations

Since we do not know the actual grid specifications, different static load are connected to take into consideration a random distribution situation, and finally the dynamic load represent the presence of 25 km dynamic wireless charging lane with 34 MW capacity. Since the simplified model consider two charging station, the maximum allowed power is at 17 MW per station.

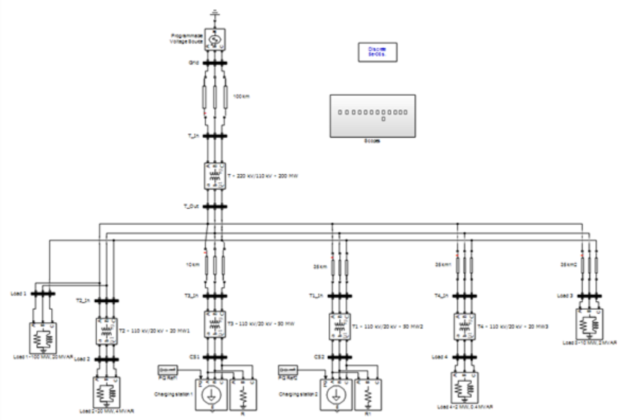

Figure 8: Grid infrastructure within charging station area

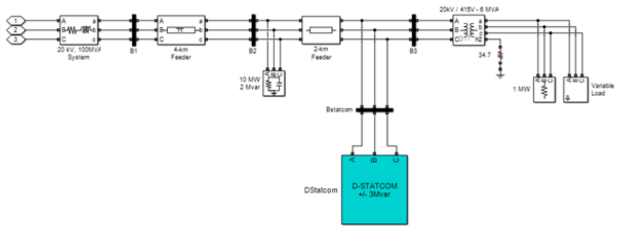

Figure 9: Charging station detailed components

In Figure 8, a 220 kV grid source is powering a 220kV/110kV transformer, which is connected to several loads, and several distant 110kV/20kV transformers. The two charging stations are connected to two transformer outputs. The feeder between the two charging stations is equivalent to 25 km transport cables, and several loads are connected to 110 kV and 20 kV distribution systems.

Each charging station has the equivalent circuit described in Figure 9, where we are connecting some static loads, a D-STATCOM, which will be used later, and finally the variable load, which is equivalent to EVs load connected to the charging station.

Grid impact of high integration on EVs

We have configured the simulation with load oscillation (variation of connected EV's number) between 4 and 6 seconds. Load oscillation profile is represented in Figure 10, and we can notice that voltage level is also oscillating; taking the shape of a sine wave, indicating that EV's number is decreasing, then increasing before returning to its original value. In addition, we have included a voltage swing of $\pm 9\%$ between 1 and 3 seconds, imitating voltage oscillation due to other connected loads. It is clear from the results that high integration of EVs will results in voltage oscillation, mainly due to reactive power oscillation, and the variation of active power can leads to frequency oscillation. Using Matlab Simulink® will not allow us to see these frequency oscillations, as the power source is already equipped with internal frequency regulation.

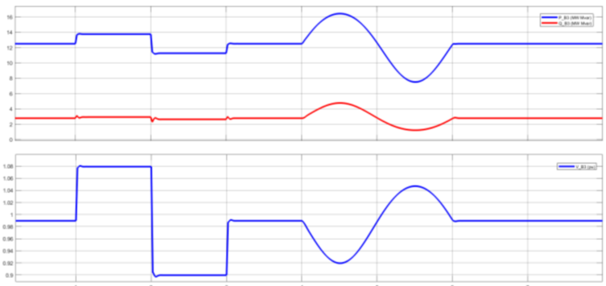

Figure 10: load's active and reactive power, and voltage (pu) without regulation

GRID IMPACT REDUCTION TECHNIQUES

As mentioned before, this paper deals only with the use of D-STATCOM. Here we are using the D-STATCOM in two modes: reactive power compensation, and voltage regulation.

Reactive power compensation

The D-STATCOM circuit is a controlled three-phase inverter with LCL filter, and a capacitive bank. The control allows injecting or absorbing reactive power.

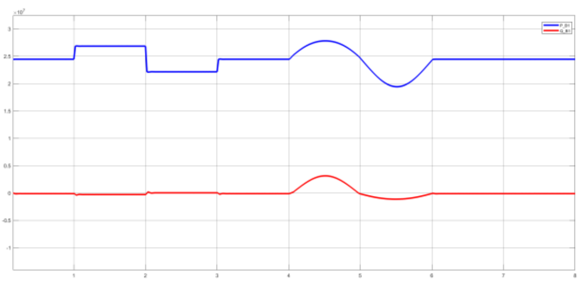

Figure 11: Active and reactive power with reactive power compensation

First, we measure reactive power in the circuit, and use it as an indication to create a quadratic current reference. The direct current reference is created by capacitor voltage error from desired value. As we can see in Figure 11, the reactive power absorbed from the grid is reduced by 3 MVAR. This is due to limiting the capacity of the D-STATCOM to 3 MVAR. While this solution prevents high increase in reactive power, and then limits current and losses, and improves power factor, in some cases the voltage level will still drops due to high active power absorption. This explains the need of direct voltage regulation described in next paragraph.

Voltage regulation

The same circuit is used here, but reactive power injected into the grid is a function of voltage level. As shown in Figure 12, we are using a 3 level hysteresis control, which injects 3 MVAR reactive power when voltage is below 98%, and absorb reactive power when voltage is above 102%. The process will continue until voltage returns to 100% original value.

In Figure 13, notice the injected and absorbed reactive power (in red) from the D-STATCOM. Notice also how voltage is closer to 100%. Again, the 3 MVAR was not enough to maintain exact 100% voltage, but allows a reduction of almost 4% of the voltage level.

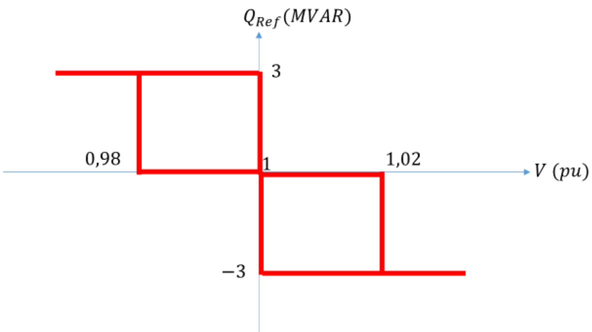

Figure 12: Reactive power reference v/s voltage (pu)

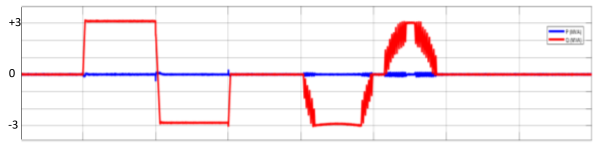

Figure 13: load's voltage (pu), and D-STATCOM active and reactive power with regulation

CONCLUSION

In this paper, we have represented the whole WPTS for charging EVs, with its connection to the grid, and the D-STATCOM used for voltage regulation and reactive power compensation.

The model is still in early study stage, as so the implementation process, but having a first look of the expected results will benefits in future improvements. In addition, due to model structure and with future knowledge of project used component, it will be easier to adapt the model according to project's purposes. The D-STATCOM have been used to regulate voltage level, and it is possible to use the same infrastructure to regulate frequency by injecting or absorbing active power from BESS.

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