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Dynamic wireless EV charging system design for efficient e-mobility

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Executive Summary

Dynamic wireless EV charging or on the move EV charging enables power transfer between the energy system and vehicles over the air, based on resonant inductive coupling between coils installed in the infrastructure and vehicles. It decreases EV battery size and associated costs while at the same size it extends range. No journey idle time for recharging and physical contact with charging cables is required, thus dynamic charging enables uninterrupted commute for EV drivers. A multitude of functions are required to implement and furthermore commercialize such systems; power transfer efficiency optimization, booking, payment and billing, power system integration. Novel challenges, stemming from the nature of dynamic wireless power transfer, span all functions and require a reconsideration of both charging infrastructure and EV design.

1 Introduction

Electrification of transport has been identified as a necessary development leading to economic and environmental friendly energy consumption. According to [1], well-to-wheel primary energy consumption of a reference fuel consuming vehicle is 522-750 Wh/km, while consumption of an electricity consuming vehicle is 457-492 Wh/km. Convergence of alternative source energy production and vehicle electrification is pre-requisite in cutting CO_2 emissions. Total CO_2 emissions of a conventional Internal Combustion Engine (ICE) are 145-215 g/km while electric vehicle emissions vary between 8-140 g/km depending on the energy production mix. The EU has set a 80% de-carbonization goal by the end of 2050. It is indicative that in order to achieve this goal, 95% transport de-carbonization is required. Electric Vehicles (EVs) among other vehicle technologies will contribute towards this direction [2]. Electromobility promises de-carbonization of transport at the same level of driving experience offered by conventional automotive solutions [3]. Additionally larger EV fleets can foster renewable source integration within the energy mix, since more storage systems would be interconnected to the grid [4]. Moreover, processes optimizing power consumption without exceeding grid generation limits can enhance grid stability and ensure sound operation of the system [5]. Dynamic wireless charging (DWC) can further decrease EV market introduction barriers as it provides additional virtues to EVs; smaller batteries and travel comfort are such attributes.

During DWC EVs can travel at constant or variable speed typically in a devoted special lane that hosts the charging infrastructure. EVs are recharged while travelling without the need to stop for recharging. Advantages of the process include reduced battery size, increased EV range and more convenience for the driver. FABRIC [6], a European FP7 research program, addresses the technological feasibility, economic viability and socio-environmental sustainability of dynamic, on-road charging of electric vehicles. It assesses the integration of electric vehicles in the transportation system through the use of innovative dynamic wireless charging technologies which could remove drawbacks of current charging solutions. Moreover, during FABRIC, vehicle to road and grid infrastructure systems have been conceived and analyzed, in order to support the deployment of these solutions. FABRIC essentially aims at defining and characterizing critical technological domains that will escort dynamic charging to viable wide European deployment, such as driving assistance for charging, grid energy management systems, road installations, by quantifying benefits and costs.

The scenarios of use for the three types or modes of FEV charging covered in FABRIC are the following:

1) Static charging: typically the vehicle is parked for a long period of time (hours), either privately (home, garage, etc) either at a public parking lot. However fast charging could last less than an hour [6].

2) Stationary charging: The EV charges for limited amount of time that typically lasts from seconds to minutes. Charging spots are usually installed in road segments where cars wait for a limited amount of time (in front of traffic lights, etc...).

3) Dynamic charging: EV's charge while in motion on a dedicated charging lane consisting of successive charging pads (Figure 1). Continuous charging time typically lasts from ms to secs depending on the speed of the EV and the layout of the charging lane. FABRIC aims at addressing open issues of dynamic charging and assessing the feasibility of it's deployment, therefore this mode is an essential aspect of research performed in FABRIC.

2 DWC system concept as designed in FABRIC

The DWC system concept proposed by FABRIC consists of two solutions; off board and on-board. The off board component comprises power electronics and ICT modules of the charging infrastructure whereas the on board component includes sub components of the EV. The system level concept is depicted in the following image

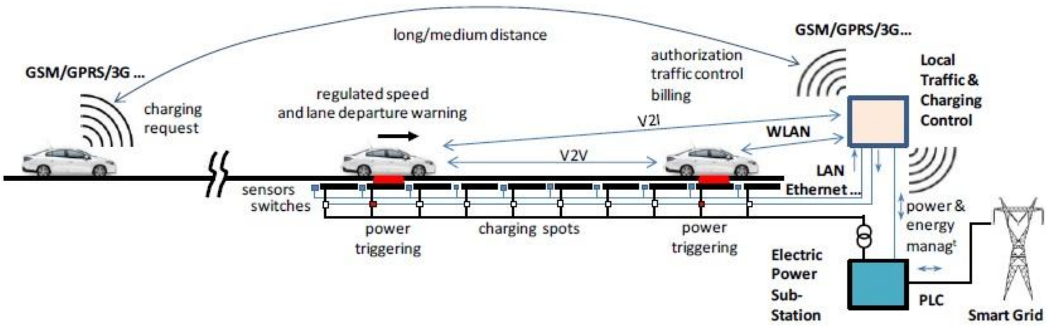

Figure 1 System level DWC concept

As depicted the system consists of a multitude of functionalities including Advanced Driver Assistance Systems (ADAS- Speed regulation and vehicle alignment), charging authorisation and billing, power electronics for high efficiency power transfer and smart grid ICT that enables reliable operation within the power system. The aforementioned services are integrated in an interoperable manner, in the following test sites.

6.1 Italy (Torino)

The test site in Italy, located close to A32 Motorway Torino – Bardonecchia (managed by TechnoSitaf),will be designed in order to be reconfigurable (at low cost) for testing any existing and future on road charging technology. In particular, it is envisaged to design and install switch board and electric power line as well as buried cables in order to guarantee a plug & play approach for new technologies. The FABRIC test bed will be designed and constructed in accordance with safety guidelines and standards toprovide at least 260 m of electric car and LDV dynamic charging infrastructure Some features of the test site include

1. Traffic information capabilities
2. Management of electric vehicles
3. Vehicle detection
4. Evaluation equipment
5. Simulation of urban and extra-urban environment
6. Electric power supply: > 50kW

Two charging systems will be deployed in the Italian test site; 1) Custom charging system developed by POLITO (Polytechnico Torino), 2) Solution provided by SAET SPA.

An overview of the design proposed by POLITO is provided in the following image.

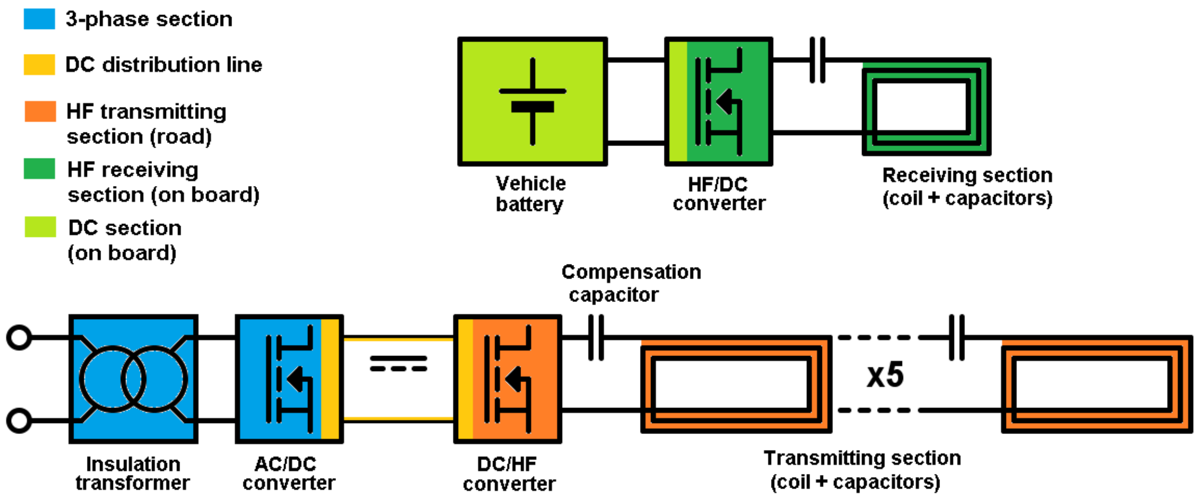

Figure 2 Wireless charging design (POLITO)

Contrary to other implementations that are based on a high constant current on the transmitting side, the solution proposed uses high voltage power transmission with a relative low current value led by the electronic switches. The entire system, is supplied by a 3-phase insulation transformer in order to manage the system protection of the transmitting side with a IT grounding where the electrical equipment are independently grounded off of the power source. 3-phase AC/DC MOSFET-based converters provide for a stable supply of a DC distribution link where several DC/HF converters can be connected. The DC/HF converter is the power electronic source of the transmitting coils that form the charging lane for dynamic charging when installed sequentially. The solution is scalable and more DC/HF converters can be installed to extend a charging lane or create several charging lanes in parallel.

A MOSFET solution is proposed also for the DC/HF leg due to its linearity in the output voltage drop and the fast switching capability. This structure, supplied at 650V and with a maximum power transfer of 20 kW, presents reduced size and the elimination of additional inductive components. Another innovation key point of the POLITO system is the adoption of a MOSFET H bridge solution for the receiving side control and the vehicle battery interfacing as well. Having dual active control at each side of the inductive transmission adds flexibility to the system control and increases its robustness while facilitating interoperability with different kinds of receiver coil geometries and different battery technologies installed on board of the electric vehicle.

The SAET SPA proposal aims at a low cost system based on a very simple field coil constituted by a substrate of a “magnetic” material able to concentrate the magnetic flux towards the top of the coil where the car is passing. SAET solution comprises coils supplied by load-resonant power frequency converters operating at a frequency range of 10-150 kHz and a pick–up system on board of EV. The resonance frequency depends on the geometry of the field and pick-up coils system and the operating power.

The dynamic wireless charging prototype has been developed [7] and integration of the test site will is in it’s final phase.

6.2 France (SATORY)

The French test site is located in SATORY near Versailles, a facility dedicated to testing and qualifying intelligent transportation systems, either fully embedded in vehicles (i.e. driver assistance systems) or distributed between vehicles and roads (cooperative systems). The dynamic solution tested by VEDECOM is based on the QUALCOMM static wireless charging solution already announced and trialled in London since 2013. The solution concept was originally created for dynamic charging for industrial applications such as materials handling and is actively used in many car factories.

The innovation lies in the extension of the technology to higher speeds and to a more uncertain environment with varying vehicle speeds, heights of vehicle coil above road level, vehicle energy requirements and vehicle alignment. In addition, the control technology must consider maximum grid network power limits, and power quality requirements. Finally, the system must have the capability to transfer data such as vehicle ID for electricity payment, and information to the car’s computer for advanced services for the driver such as range prediction. The coils are installed in a 100m test track and the power transfer rate is 20kW. The dynamic wireless charging trials have commenced since May 2017. [8]

3 System integration and novelty paradigms: Smart grid

Dual side active control of the power transfer process from both the on-board and off board modules activates additive value services such as Demand Side Management [7]. By modulating the amount of power received from the vehicle’s side in an adaptive manner that is consistent to dynamic charging, EVs can develop charging strategies according to financial criteria. Moreover, the charging infrastructure itself can be interfaced to Demand Side Management interfaces of the power system’s Distribution System Operator, thus ensuring that dynamic wireless charging infrastructure does not result in deterioration of power supply quality due to peak loads. Moreover, the same Demand Side Management interface of the charging infrastructure can be integrated with the Energy Retailer in order to ensure that aggregated energy consumption follows margins defined according to the respective contractual agreements at the wholesale energy market level. Figure 3 summarizes the approach. The dynamic wireless charging (DWC) infrastructure takes real power constraints into account according to power quality criteria managed by the Distribution System Operator (DSO). These constraints ensure that line capacity and voltage deviations are within tolerable range, thus ensuring power system quality and extending component lifetime. Moreover energy efficiency constraints are also taken into consideration by the charging infrastructure. The energy retailer sets maximum active power limitations, thus ensuring system operation within economically viable states.

One of the charging processes that have been under extensive study the past years is the charging management, meaning the creation of a charging profile for each EV in order to satisfy the aforementioned technical and cost constraints imposed by the grid (Demand Side Management), the charging infrastructure operator, the EV battery system and the EV user. Many approaches and optimization methods can be found in the literature for static charging. These focus mainly on shifting the load of EV charging to off-peak hours leading to lower cost for the user and lower strain for the grid. Standards have been updated to take into account these interactions and the variables that are necessary to calculate the optimal charging schedule. However during dynamic charging, the EV charges for a very short duration of time which ranges from seconds to minutes (depending on the EV speed and the charging lane length) while the contact time between the EV and each charging pad is just some milliseconds (again depending on the EV speed). The conventional methods for charging management cannot be applied while new variables need to be considered for inclusion by the future standards in order to enable Demand Side Management under dynamic charging conditions. In FABRIC this issue has been investigated and a method that is inspired by network traffic management was proposed. Network rate control algorithms as introduced by [9], provide a framework for distributed optimization of charging rates under dynamic communication networks. Rate control algorithms typically are implemented according to the following schemes

- Additive Increase Multiplicative Decrease
- Price based charging rate modulation

In Additive Increase Multiplicative Decrease deployments, EVs additively increase their charging rates to the maximum charging rate possible, whereas they multiplicatively decrease their power once a congestion event is received through the dedicated DSRC (Dedicated Short Range Communications) interface. In this case the Road Side Unit (RSU) transmits a broadcast signal indicating the need from vehicles to modulate power once the overall demand of the lane overcomes the supply or limits provided by the Energy retailer or DSO. The system's response for a 1km charging lane setup is depicted in Figure 4. The system adapts to new constrains provided by the energy retailer-DSO within the sub-second range.

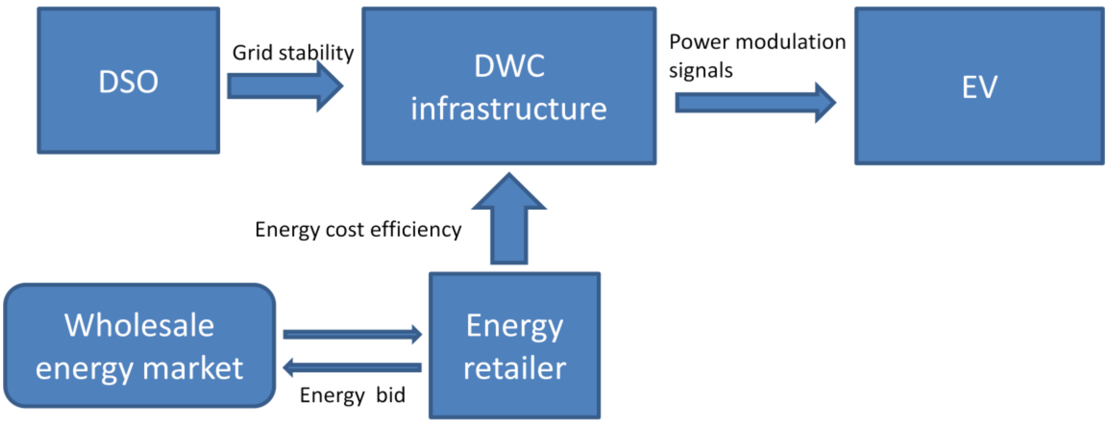

Figure 3 Demand Side Management integration for DWC infrastructure

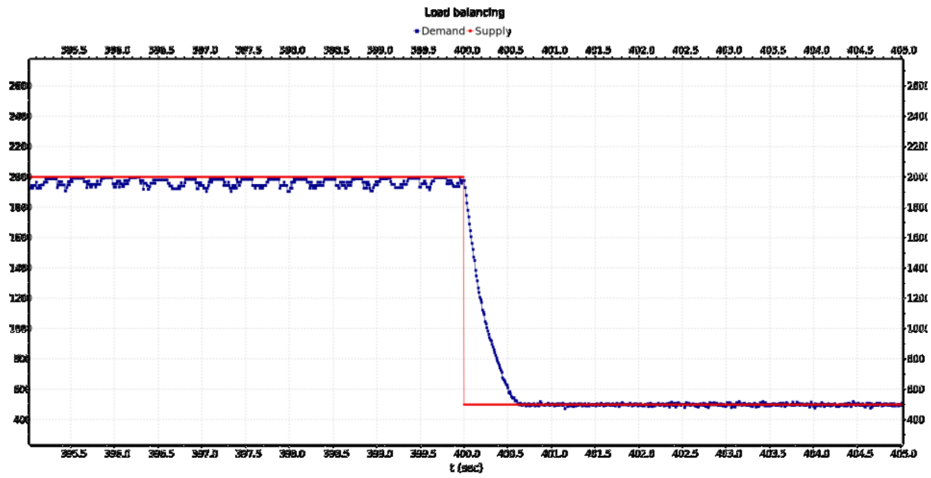

Figure 4 Convergence of DSM for a fleet of vehicles

On the other hand price based charging rate modulation additionally provides the possibility to differentiate charging allocation to vehicles according to a willingness to pay criterion, thus ensuring that vehicles can be charged with priority given an increasing order to of willingness to pay criteria. Such a mechanism for DSM, enables various business scenarios that benefit from the increased interconnectivity of systems holistically targeting cost efficiency. Deployment of such services is critical in reducing costs associated to dynamic wireless charging, thus enabling viable business scenarios that will pave the way towards dynamic wireless electromobility.

4 Conclusion

DWC has the potential of easing introduction of EVs to the market by supporting increase in EV range and driver comfort. Feasibility analysis performed within the FABRIC project, highlights the importance of a systematic approach to the associated charging while driving operations. Power electronic integration to demand side management optimisation is an example of system wide integration enabling added value services to both EV end users and the power grid. Similar findings in other domains such as billing, booking, payment and driver assistance systems have been identified and will be further presented and analyzed. Complementing dynamic wireless charging systems with services that target cost efficiency is essential in addressing increased charging infrastructure deployment costs [10].

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