A 30 kW Dynamic Wireless Inductive Charging System for EVs

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Keywords

≪Charging infrastructure for EV´s≫ ≪Wireless power transmission≫, ≪Contactless Energy Transfer≫, ≪Resonant converter≫, ≪Converter control≫.

Abstract

This paper presents a solution for real-time charging of electric vehicles along the road while moving. This is called the Dynamic Wireless Inductive Charging System (DWICS) and can mitigate the cost of the charging infrastructure, the size/weight/cost of batteries, and hence improve the cost and range of electric vehicles. This solution has the advantage of creating a common road infrastructure shared by cars, buses and trucks and presenting a high energy efficiency. In this work, a $30kW$ DWICS for electric vehicles is presented with an efficiency up to 90%. It is developed the overall scheme, its mathematical model, control scheme, simulations, and experiments, showing this solution is viable for future electric roads.

1 Introduction

Nowadays, energy transition is a very important point to consider and discuss in different political, public and techniques-scientific forums. Industry and transport sectors are changing towards increasingly electrification, energy efficiency, safety, cleanliness and economic competitiveness.

More efficient and less polluting, electric vehicles become a popular alternative to fossil-based transport. However, their autonomy, range, price, and acceptability are the main stumbling block to their promotion.

The charging infrastructure is a weak point in most countries and is a major concern and problem in countries that do not have rules and standardization of charging stations yet [1, 2].

The electrification of heavy-duty vehicles is facing important battery problems, concerning size, weight, and cost. Recycling and raw materials consumption are yet others challenges for such vehicles. With the deployment of adequate charging infrastructure, the size of the battery can be reduced or even be modular.

A fast-charging station network outside the roads is the obvious solution to face these problems, however, static charging stations are not the ideal solution. They implicate in long recharging time, parking lot congestion issues, they do not obtain a large reduction of battery size, they need heavy charging cables, high power local substation, open the path for vandalism and safety, among other problems.

Another solution, named Dynamic Wireless Charging, is one of the three technologies considered in a study made for the French Ecology Transition Ministry regrouping many industry stakeholders, universities, and research institutes to define the French strategy for the Electric Road Systems (ERS). The final report presents and concludes that the wireless charging solution is the best solution in terms of interoperability, carbon consumption, and security, but is the less deployed for high power energy transfer. Other carbon-free technologies were considered, like hydrogen, but battery-based electrification has been the final choice.

This work presents a Dynamic Wireless Charging System (DWCS), that allows any kind of vehicle to be charged while driving on an adapted road. The presented system will be implemented in a real environment for an urban scenario for INCIT-EV project, in Paris in 2022. The total power system installed will be up to 120kW. Two light vehicles and a light-duty vehicle will be recharged up to 30kW and 90kW respectively in dynamic, semi-dynamic, and static situations. The technology of the ground system has no limitation on the size of vehicle or its speed. It can be further installed in heavy-duty size vehicles without any change on the ground infrastructure.

2 System description

A Dynamic Wireless Charging System is composed of a static primary subsystem under the ground and a mobile secondary subsystem inside the vehicle as described in figure 1.

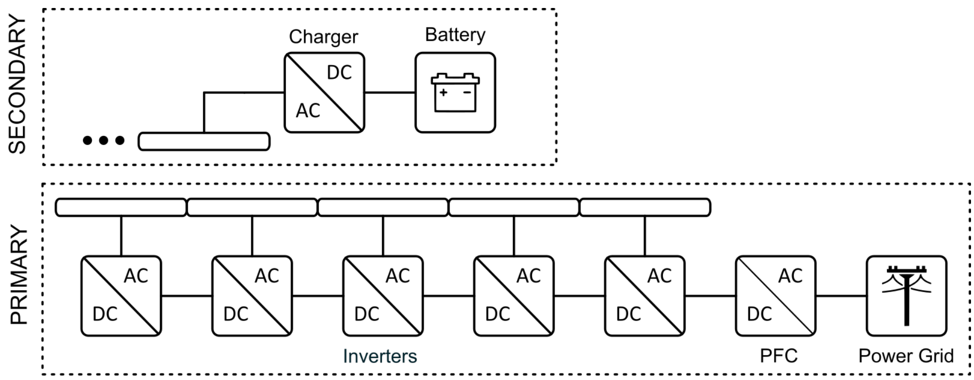

Fig. 1: Dynamic wireless charging system components.

The primary side is composed of side-by-side coils powered by DC/AC resonant converters working up to 100kHz. These converters are powered by a DC bus provided by an AC/DC grid converter with power factor correction.

The secondary system is composed of one or many coils connected to an AC/DC converter. This converter is a composition of an AC/DC rectifier and a DC/DC converter to adapt the current and voltage to the battery state of charge. The DC/DC is also responsible for the power control transfer defined by the vehicle.

The coils on the ground and inside the vehicles are the same for the presented system. The symmetry is an advantage in terms of system modeling and costs. Their dimensions were chosen to keep them completely covered by the vehicle during the charging section and avoid electromagnetic field emissions outside the vehicle limits. These coils will be completely integrated into the ground by an industrial road construction procedure for the Paris demonstration.

The inverters will be integrated into the pavement at the roadside composing a trench all along the charging lane, invisible to the public. Each coil has its own converter associated. This lane architecture was chosen for many advantages in an urban scenario despite the first impression that it can be expensive.

A first advantage is a low distance between the inverter and the coils, this is an important aspect to avoid electromagnetic emissions related to long cables in an urban scenario.

Another advantage is the performance, in this case, each inverter can optimize the power transfer for any relative position between the coils. In this technology, as it will be shown next, the nominal power is kept the same even when the alignment between coils is at 50% (between two ground coils). In addition, this lane architecture allows performing a multi-coil system where two or more coils are activated at the same time to transfer twice or more the rated power without any oversized electronics. For that, the vehicle needs to have a number of coils related to its power needs. Therefore, the same charging infrastructure can be used by any kind of vehicle. In the context of growing vehicle electrification, Wireless Charging has been investigated worldwide as a promising disruptive technology [9, 10, 11]. Indeed it stands as an attractive alternative with aesthetic, safety, convenience, modular, clean and fully automated potential advantages. Different international standardization bodies (SAE, ISO, IEC, GB) are currently addressing the recommended practices and requirements for further wireless charging technology deployments [12].

Extension from stationary to dynamic wireless charging is another challenge that started in 1976 at the Lawrence Berkley National Laboratory where the technical feasibility of a first dynamic system was evaluated. In 1992, Partners for Advanced Transit and Highway (PATH) demonstrated $60kW$ power transfer with 60% efficiency across a $7.6cm$ air gap [8]. Since then different technologies for dynamic wireless charging have been demonstrated, and are summarized in [7].

3 Power electronics topology and modulation

The topologies of the converters were chosen to be completely bidirectional and based on the same hardware converter and SiC switches (ROHM BSM180D12P2C101). The bidirectional functionality will not be tested and will be treated at another time. The system presented don't have the DC/DC converter on the secondary but it will be considered in future works (see figure 2).

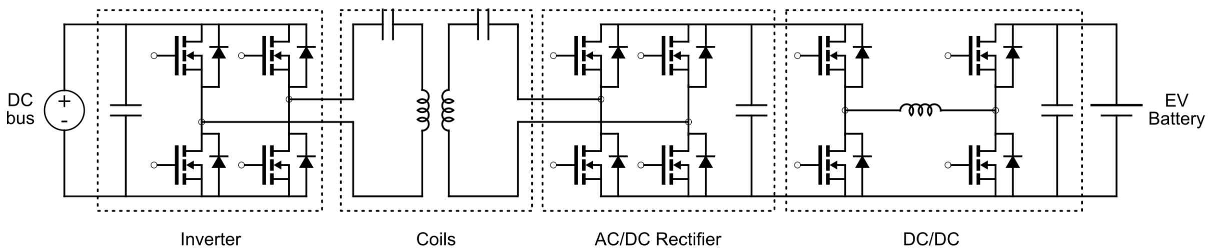

Fig. 2: Wireless power transfer system converters.

The inverter is a single-phase full bridge converter commanded by the classic bipolar modulation. Its efficiency can reach up to 99% in a standard charging section. The AC/DC rectifier is an active converter to reduce losses in the charging operation, reaching approximately the same efficiency level as the inverter.

The current-controlled DC/DC converter is bidirectional, such as to enable the charge of the intermediate capacitor between the rectifier and the DC/DC. The pre-charge of this capacitor is fundamental to avoid over-current at the system switch-on. In a charging stage, the DC/DC is commanded as a buck converter to adapt the nominal voltage (normally a little higher than the battery voltage), current, and desired power of the charging system.

4 System model

A series-series resonance circuit was chosen for this system. This topology allows us to reduce the current supported by the power converters despite the high voltage on the passive components. Figure 3 shows the simplified circuit considering only one primary coil and one secondary coil.

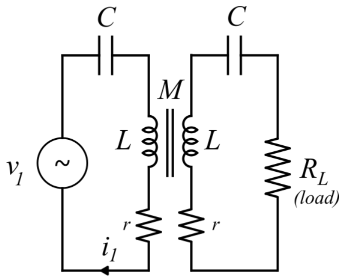

Fig. 3: Simplified two coil circuit.

The primary and secondary coils are considered equal in terms of inductance and capacitance. Therefore, from the basic circuit equations, the relation between the input voltage and primary current can be described as equation 1:

$$\frac{v_1}{i_1} = r + \frac{\omega^2 M^2 (r+R_L)}{(r+R_L)^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} + j\left(\omega L - \frac{1}{\omega C} - \frac{\omega^2 M^2 \left(\omega L - \frac{1}{\omega C}\right)}{(r+R_L)^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}\right) \tag{1}$$

Where:

v_1 is the primary output voltage from the inverter

i_1 is the primary output current from the inverter

ω is the frequency of the voltage source

M is mutual inductance between the primary and secondary coil

r is the self resistance of the coil

L is the self inductance of the coil

C is the resonance capacitor

R_L is the load resistance representing the secondary power demand

In the resonance condition, the imaginary part of this equation is zero, which means that the primary current and voltage are in phase. For this, the frequency to be applied to the voltage source is given by the equation 2:

$$\omega = \sqrt{\frac{-(C^2R^2 - 2LC) + \sqrt{C^4R^4 - 4C^3R^2L + 4k^2L^2C^2}}{2(L^2C^2 - k^2L^2C^2)}} \tag{2}$$

Where $R = r + R_L$. From the differential equations of the circuit, the space state model is deduced for simulation in Equation (3).

$$\begin{bmatrix} L & M & 0 & 0 \\ M & L & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{d}{dt} i_1 \\ \frac{d}{dt} i_{21} \\ \frac{d}{dt} v_{C1} \\ \frac{d}{dt} v_{C2} \end{bmatrix} = \begin{bmatrix} -r & 0 & -1 & 0 \\ 0 & -r & 0 & -1 \\ \frac{1}{C} & 0 & 0 & 0 \\ 0 & \frac{1}{C} & 0 & 0 \end{bmatrix} \begin{bmatrix} i_1 \\ i_{21} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & -1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_{rec} \end{bmatrix} \tag{3}$$

Table I shows the nominal parameters measured in the real system prototype and used for the simulations and tests.

Table I: System parameters

Nominal load power	30kW
Nominal voltage	435V
Nominal current	80A
Resonant capacitor	33nF
Coil inductance	135μH
Coil resistance	25mΩ
Operating frequency	78kHz to 92kHz
Load resistance	5.3Ω
Ground clearance	17cm

5 Control and operating mode

The resonance condition is the main target of the control strategy on the primary side. The resonance ensures zero voltage switching, reducing power losses on the inverter. In addition, under this condition, the power transfer rate is the highest possible but it still depends on the converters architecture, transistors technology, modulation and mission profile.

In a dynamic inductive charging system, the relative position between the primary coil and the secondary is constantly changing while the vehicle is moving. It means that mutual inductance and even self-inductance are changing all the time and depends on the relative position between primary and secondary coil, the speed of the vehicle and the ground clearance. Figure 4 shows the typical variation of the mutual inductance between a primary and a secondary coil versus the relative position between them. The position 0*mm* is when the coils are 100% aligned. To compensate for this variation and keep the resonance condition in every relative positions, the frequency of the primary voltage needs to be regulated.

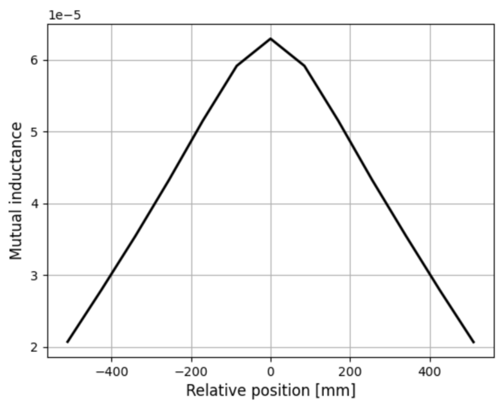

Fig. 4: Mutual inductance variation.

Different from other technologies, with the frequency regulation, the system is able to send at least the nominal power at all alignment conditions. The frequency is regulated based on the phase between the primary voltage and current. The phase error is the input for the controller that defines a reference frequency to the power inverter as described in Figure 5.

The maximum permissible latency of the phase angle detection is an important and limiting factor to define the maximum vehicle speed allowed, the system losses and the control system performance. The relation between the variation of the mutual inductance and its phase angle variation result is used as the key parameter. It means that, considering a hardware circuit phase detection, with a fixed and low phase latency measurement, the maximum latency will be limited by the allowed maximum losses on the converter related to the hard switching modulation condition. Other system specification will affect or be affected by the phase detection latency like: the pulse with modulation (PWM) resolution, the interruption frequency, the function algorithm and the maximum admissible phase error to the controller and the vehicle speed.

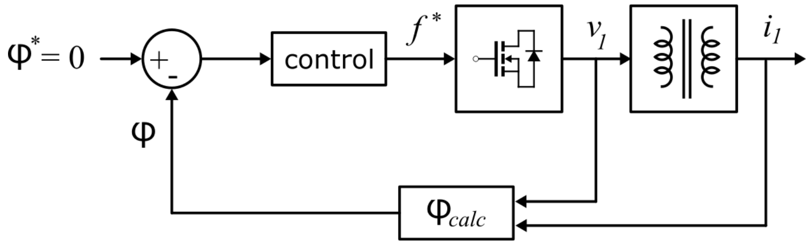

Fig. 5: Mutual inductance variation.

In the described system, only one coil on the ground is powered at each time. The coil with the best alignment is activated and it passes to the next one after a 50% misalignment. This detection is made by establishing a short-circuit on the next coil and measuring the induced current. After that, this induced current is compared with the current on the active coil to define when the system changes the state of the coils using a criteria of higher peak value.

6 Results

The validation of the system model was performed using PSIM software in a static simulation. The result is presented in Figure 6 with a $150V$ voltage on the primary side and a peak primary current at about 40A with a zero phase between then.

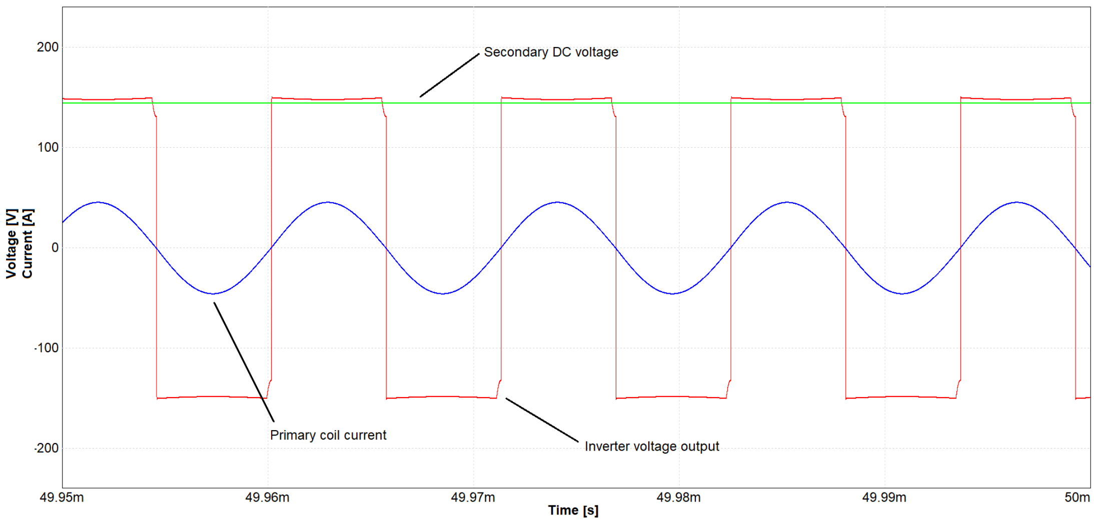

Fig. 6: Simulation result of the system model with real parameters.

This result is compared to measurements on the prototype presented in Figure 7 where the same voltage was applied and the same current is provided to the primary coil.

After the static tests made on a low voltage and power step, the dynamic behavior of the system was evaluated. The switching process, the resonant condition, and the total efficiency of the system were measured in simulation and real experiments. In Figure 8, simulation results are presented. At the beginning of the simulation, only the inverter N is active, sending power to the secondary coil. The inverter $N+1$ is short-circuited to measure the induced current. When the coils are 50% misaligned, the inverter N stops transmitting power, and inverter $N+1$ starts the energy transfer, which can be seen around $18ms$ of simulation time.

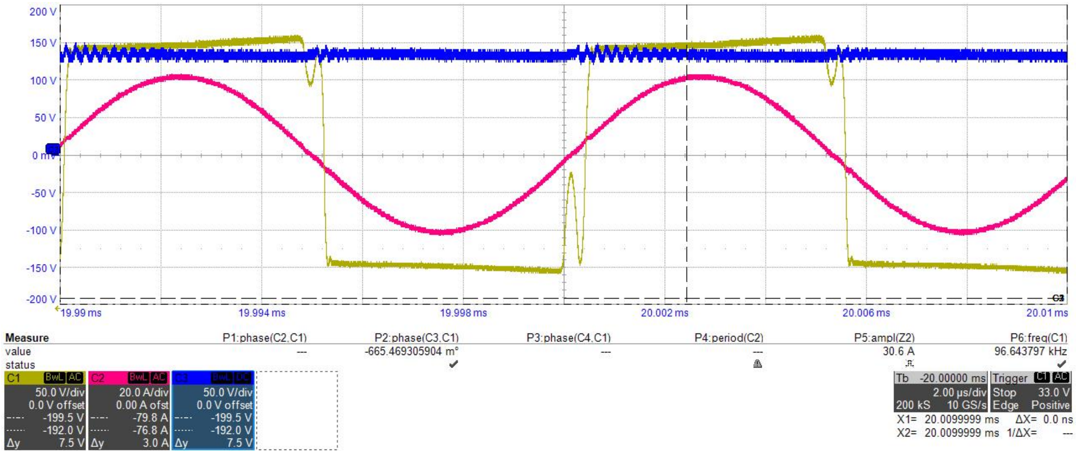

Fig. 7: Measurement of primary voltage (yellow), primary current (rose) and secondary DC voltage (blue).

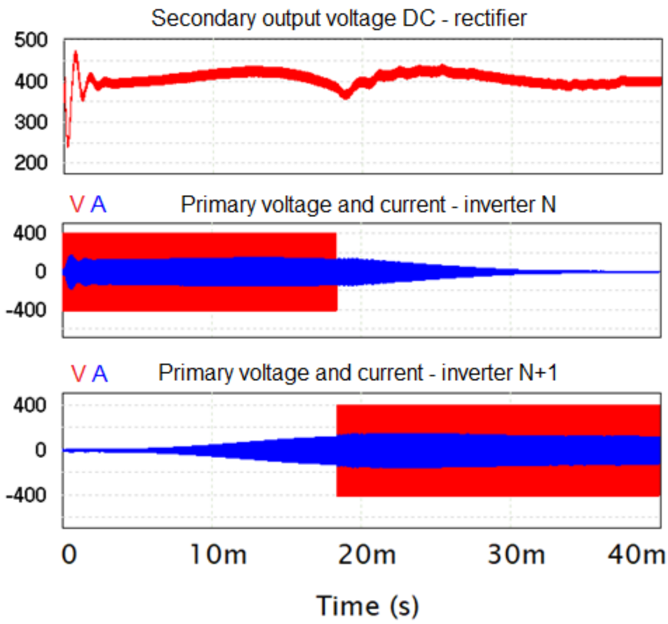

Fig. 8: Dynamic simulation results.

The experiments were performed using a wireless inductive charging systems testing bench composed of a robotic arm, power analyzers, electromagnetic field probes, and oscilloscopes, all synchronized by a supervision system (see Figure 9).

Fig. 9: Wireless inductive charging systems testing bench.

The primary coils are placed on the table forming the charging lane. While the secondary coil is attached to the robotic arm that is able to simulate the movement of a vehicle at a maximum speed of $13km/h$.

The result is presented in Figure 10 for a $30kW$ power target on the output of the system. The efficiency of the system varies between 82% and 90%, and a minimum of $30kW$ is assured at most part of the time. The instants where the $30kW$ target power is not respected, are related to a delay between the activation and deactivation of an inverter (active coil switching). The efficiency can be improved by using an active rectifier on the secondary system and improving shielding and coil design.

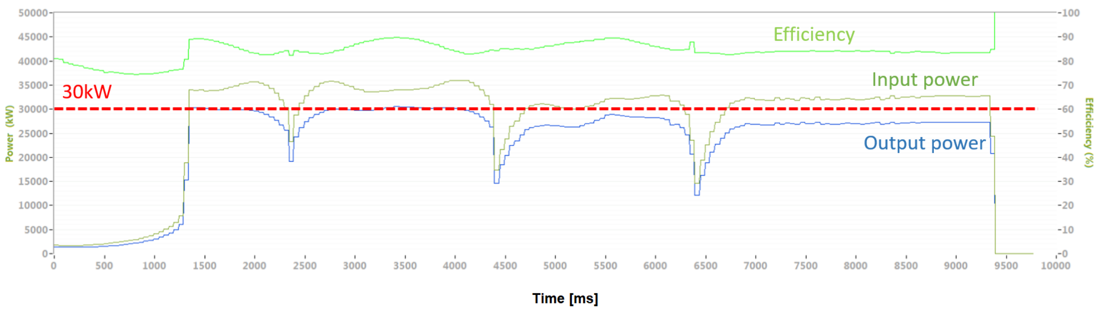

Fig. 10: Wireless inductive charging systems testing bench.

7 Conclusion

A Dynamic Wireless Charging System for electric vehicles was introduced in this paper. This system represents a good solution for reducing battery size, weight, and cost, while dramatically extending the range for vehicles, either cars or trucks (heavy-duty vehicles). This solution allows an effective energy transition from fossil fuels to electricity, even in long-range applications.

In the present work, it is proposed a simplified mathematical model, a control scheme for regulating the primary side frequency, simulations, and finally real experiments. A rather good correlation between simulation and measurement results is found for the control strategy.

This control scheme allows to keep the system in resonance, despite the movement of the vehicle, which create time-varying alignment and coupling, and as a consequence, time-varying parameters. In addition, it assures a power transfer of 30 kW with an transfer power rate up to 90% in the experiments.

Some improvements can still be made in the system to increase the performance, like using an active rectifier and optimizing the commuting process of an activated and deactivated inverter. Such steps will be carried out in future works, as well as new experiments in a real track.

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