Evaluating Dynamic Wireless Charging of Electric Vehicles Moving Along A Stretch of Highway

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Published in:
SPEEDAM 2016 - 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion

DOI (link to publication from Publisher):
https://doi.org/10.1109/SPEEDAM.2016.7525922

Publication date:
2016

Document Version:
Accepted manuscript

Citation for published version:
Garcia-Vazquez, C. A., Llorens-Iborra, F., Fernandez-Ramirez, L. M., Sanchez-Sainz, H., & Jurado, F. (2016). Evaluating Dynamic Wireless Charging of electric vehicles moving along a stretch of highway. 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2016, 61-66. https://doi.org/10.1109/SPEEDAM.2016.7525922

Evaluating Dynamic Wireless Charging of Electric Vehicles Moving Along A Stretch of Highway

Abstract—**Electric vehicles are the most promising sustainable transport technology for solving the environmental, economic and social problems associated to the internal combustion engine vehicles. The research and development of new charging methods is necessary for a further integration of electric vehicles in transport sector. Inductive power transfer is the most promising technology for dynamic wireless charging of electric vehicles, which can be used to supply the motors and/or charge the battery of the electric vehicle while it is moving. This charging system can help to reduce the size and cost of the battery, increase the driving range and expand the use of electric vehicles. This paper presents an analysis methodology of a Dynamic Wireless Charging system applied to evaluate the power and energy requirements for charging electric vehicles moving along a stretch of the A-381 Highway in Cádiz (Spain). The study shows the great dependency of the energy transferred to the electric vehicles with the speed and the great variability of power and energy requirements related to the daily traffic.**

Keywords—electric vehicle; wireless power transfer; battery; dynamic charging.

I. INTRODUCTION

Nowadays, transportation sector is increasing rapidly around the world. This sector predominantly uses internal combustion engine vehicles (ICEV) based on liquid fossil fuels that supply 95% of the total energy consumed by world transport [1]. This heavy dependence on fossil fuels is causing environmental problems (high air pollution and greenhouse gases emissions) and problems of economic and social sustainability. For these reasons, new sustainable transportation systems are need.

In this scenario, electric vehicles (EV) are considered a viable and sustainable transport technology for solving the problems associated to ICEV. In fact, current global EV stock (through end of 2014) is over 665,000 (that represents 0.08% of total passenger cars). The International Energy Agency estimates that the EV stock will be over 20 million (2% of total passenger cars), including plug-in hybrid electric vehicles and fuel cell vehicles, by 2020 [2], and that almost 80 percent of automobiles sold in 2050 will be EV [3]. However, several barriers are hampering further development and use of EV. One of the most important components of an EV is the battery, which is the main limitation of current EV. The current batteries of the EV present high cost, short lifetime, short driving range and excessive charging time when compared with ICEV [4]. These problems need to be solved and new technological solutions must be developed in order to achieve a further integration of EV in transport sector. The current research is focused on developing new batteries and new charging methods [5].

Wireless charging can help to overcome the problems associated to the driving range and charging time of EV. The most promising technology for wireless charging of EV is based on Inductive Power Transfer (IPT). It uses primary coils located in the charging station to transfer induced power to the secondary coils of the EV, which can be used to supply the motors and/or to charge the battery of the EV. IPT allows to transfer high power, presents high efficiency, and is reliable and maintenance friendly [6].

Wireless charging can be stationary or dynamic. Stationary charging is performed with the EV stopped at public and private parking areas, while dynamic charging is carried out with the EV moving on sections of road. Stationary charging presents lower cost, but it needs larger size of battery to store more energy and to increase the driving range when compared with dynamic charging. Dynamic charging, which uses several primary coils embedded in the track to transfer induced power to the secondary coils of the EV while it is moving, can help to reduce the size and cost of the battery, and increase the driving range [7].

In this work, the dynamic charging of EV moving along a highway stretch by dynamic wireless power transfer (DWPT) system is evaluated. The remainder of the paper is organized as follows. Section II reviews the dynamic charging concept of EV by DWPT. Section III describes the case study evaluated in this work, in which the traffic data, the technical characteristics of the EV (Nissan Leaf) and the DWPT system under study are detailed. Section IV presents the analysis methodology applied and the results obtained for the case study. In particular, the power required by the entire DWPT system, the energy transferred to the EV, consumed by the EV and stored in the batteries of EV along one day are calculated and analyzed. Finally, Section V outlines the conclusions that can be derived from this work.

II. DWPT FOR ELECTRIC VEHICLES

Wireless Power Transfer (WPT) is considered as the transmission of electrical power from a source to a load without using electrical wires connected between them. Early work on WPT were made by Nikola Tesla at the end of 19th century [8], but its safe and efficient implementation could not take place until today.

WPT technologies (laser [9], photoelectric, radio waves, microwaves [10], inductive coupling and magnetic resonance coupling) can be categorized taking into account several aspects. If power transfer distance is considered, these technologies can be divided into two types: near field WPT (NF-WPT), when the transfer distance is smaller than the wavelength of electromagnetic wave; and, far field WPT (FF-

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This work was partially funded by the Spanish Ministry of Economy and Competitiveness (Grant ENE2013-46205-C5-1-R).

WPT), when the transfer distance is longer than the wavelength. Frequencies of FF-WPT are in GHz range, while frequencies of NF-WPT are in kHz-MHz range. In both types, efficiency deteriorates exponentially with the transfer distance.

Inductive Power Transfer (IPT) is the WPT technology most used in EV charging [6]. Essentially, IPT is based on inductive coupling between two coils with air core. Fig. 1 shows the typical block diagram of an IPT system. Transmitter coil (L1) is driven by a high frequency oscillator. According to Faraday's law of induction, time-varying magnetic fields induce electric induced voltage in the receiver coil (L2) which is placed closer to L1. Electric power is applied to the load (the battery) by using a rectifier. In order to reduce the leakage flux due to the air gap, compensation capacitors are used in conjunction with both coils (primary and secondary). Both LC circuits are designed to work at the resonant frequency in order to enhance the transfer of energy. In this case, the system is called Inductive Coupled Power Transfer (ICPT).

Compensation capacitor can be placed in Parallel (P) or Series (S) with their respective coil. Taking into account the connection of the capacitor in each winding, four topologies arise: Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP). It can be probed that if parallel compensation is used the adequate capacitance value depends on the coupling coefficient between coils. In EV charging applications, coupling coefficient is not a constant, so that SS compensation is preferred in this case.

Kirchhoff's voltage law applied to the equivalent lumped circuit of the system can be used to calculate adequate values of the components in order to obtain the Maximum Power Transfer (MPT) operation point of the system [11]. The MPT always occurs at the resonance frequency of both coils. In the transfer efficiency analysis of this system, both the power transferred to the load and the input to the output efficiency have been used as the figure of merit.

A. *WPT types in EV charging systems*

At present, EV charging methods can be categorized in two types: wired-EV charging systems and wireless-EV charging systems. Wireless-EV charging systems has some advantages compared to wired-EV charging systems. Current state of art of wireless-EV charging system technology allows power transfer distances at several centimeters. However, there are still several challenges to overcome: power transfer efficiency, safety consideration, misalignment tolerances, etc.

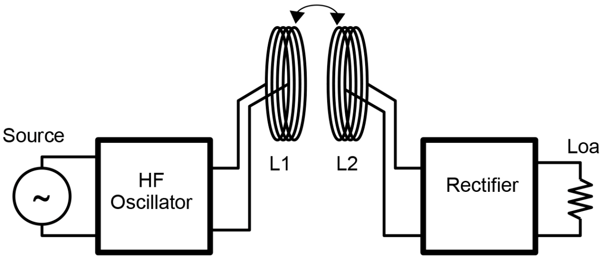

Fig. 1. Block diagram of a IPT system

WPT system can be used for EV charging in two different ways taking into account the movement of the vehicle:

- *Stationary WPT charging systems*. In this case, the battery of the EV is charged while the vehicle remains in the charger area. Usually low frequency utility power is converted to high frequency power by a one stage (AC-AC) or two stage (AC-DC-AC) converter. This power is applied to the primary coil. Power is transferred to the secondary coil, and then it is rectified in order to charge the battery [12]. This system usually has lower cost compared with the other option.
- *DWPT charging systems.* Here, the charging process is carried out while the vehicle is moving [13]. One of the main advantages of this system is that the battery state-of-charge (SOC) is not a problem in long driving distance. On the other hand, this charging system requires an expensive infrastructure. In addition, the energy transferred to the battery depends on several factors: speed of the vehicle, size of the charging system, etc. Basic configurations of this system are summarized in next paragraph.

B. *Overview of DWPT charging system*

DWPT charging systems can be divided into two categories based on the topology of the transmitter side: single transmitter track and segmented transmitter array.

In the case of single transmitter track, the primary power source is connected to a long transmitter coil buried in the track. The receiver coil, installed in the vehicle, is much smaller than the length of the track. The main advantages of this system are given next. Only one source is necessary to be connected to the transmitter, and therefore, the control system of the source is easier. When the vehicle is moving along the track, coupling coefficient between coils is nearly constant, and the movement of the vehicle fairly affects to the coupling parameters. Some disadvantages arise in this system. Due to the different lengths of the primary and secondary coils, three drawbacks appear: there are electromagnetic fields radiated outside the coupled region that can be harmful; compensation capacitor or the primary must be distributed along primary coil length; and, the coupling coefficient is low so that the efficiency of the transfer of the energy decreases.

In the case of the segmented transmitter array, the WPT system has several coils buried in the track that can be connected to the primary power source. The closest coil, or group of coils, to the vehicle is connected to the power source, then, in this topology, it is necessary to know the position of the vehicle relative to the track. In this system, electromagnetic field radiated is minimized and distributed compensating is not necessary. On the other hand, the control of the feed of the primary coil is more complex because it is necessary to know the relative position of the vehicle and to switch the adequate coil with the source. Another drawback arises in this system. Distance between coils must be optimized in order to achieve a fairly constant charging process.

III. CASE STUDY

This section presents the case study used in this work to evaluate the power and energy requirements for the dynamic charging of EV moving along a stretch of highway.

A. Stretch of Highway

One single lane of 7.3-kilometre-long section of the A-381 Highway in Cádiz (Spain) has been considered in the study. This stretch begins after leaving the A-7 Highway towards Jerez and surrounds the village of Los Barrios. The speed is limited to 100 km/h in the first part and 120 km/h in the rest.

B. Traffic data

The traffic data have been taken from a traffic sensor (A-381Pk87.5C) [14], which provides historical information about density, speed and light vehicles percentage in the road.

These data do not only depend on the time of the day but also the day of the week and the month. Therefore, a representative weekday with the highest traffic density has been chosen. The traffic data are shown in Table I.

C. Electric Vehicle

Among the wide variety of EV, the Nissan Leaf, which is a typical modern family car, has been considered as representative light EV and used in this case study.

The Nissan Leaf is equipped with a 24 kWh Lithium-ion battery and a quick charger up to 50kW. The maximum engine power is 80 kW, and represents the maximum charge/discharge rate.

TABLE I. TRAFFIC DATA

Hour	***DGT - Traffic sensor A-381 Pk 87.5 C***		
	Traffic Density (Veh/h)	***Speed (km/h)***	***Light Vehicles Composition (%)***
00:00	*36*	*96*	*100*
01:00	*24*	*92*	*100*
02:00	*34*	*98*	*100*
03:00	*42*	*90*	*100*
04:00	*50*	*92.5*	*100*
05:00	*65*	*83*	*92*
06:00	*268*	*91*	*87*
07:00	*232*	*92*	*92*
08:00	*460*	*87.5*	*90*
09:00	*380*	*83*	*95*
10:00	*308*	*83*	*91*
11:00	*260*	*89*	*87*
12:00	*258*	*87*	*73*
13:00	*236*	*89*	*76*
14:00	*250*	*90*	*92*
15:00	*212*	*91*	*85*
16:00	*262*	*89*	*97*
17:00	*240*	*90*	*93*
18:00	*236*	*88*	*87*
19:00	*224*	*85*	*92*
20:00	*210*	*87.5*	*95*
21:00	*117*	*88*	*100*
22:00	*89*	*92*	*100*
23:00	*68*	*94*	*100*

The Nissan Leaf power requirements were taken from the Advanced Vehicle Testing Activity of the Idaho National Laboratory (AVTA-INL) [15]. Fig. 2 shows the energy consumption at different speeds from a 16,000 miles' test with 18% of total driven in highway.

Although the energy consumption at low speed is high, it decreases with the speed until 48.3 km/h and remains constant below 88.5 km/h.

D. DWPT system

Based on the available information, it is apparent that there are different topologies that can be used in the layout of DWPT systems [16].

The selected layout consists of a lane with consecutive power transfer segments. Each one is composed by three coils of 8 meters' long spaced by a 5 meters' gap. The distance between segments is the same as the gap. Due to the type of lane, a considerable safe distance from the vehicle ahead is needed. For this reason, only one EV can be energised in the same segment.

The secondary coil, mounted beneath the vehicle chassis, can receive up to 40 kW from the primary coil. Some of this power is used for traction and the rest would be used to charge the battery.

Each roadside segment is supplied by a high frequency inverter from a 1.5 kV MVDC network. Thus, the modularity and system effectiveness is increased.

IV. ANALYSIS METHODOLOGY AND RESULTS

This analysis is based on the assumption that the DWPT system is not a battery charger as a Stationary WPT does. Instead, it provides energy to the motors of VE during the power transfer stretch and also charges the battery, increasing vehicle autonomy.

A. Traffic Data Analysis

As can be seen in Table I, the selected stretch has a traffic flow that varies from a maximum of 460 vehicles per hour in the morning and a minimum of 24 vehicles per hour in the

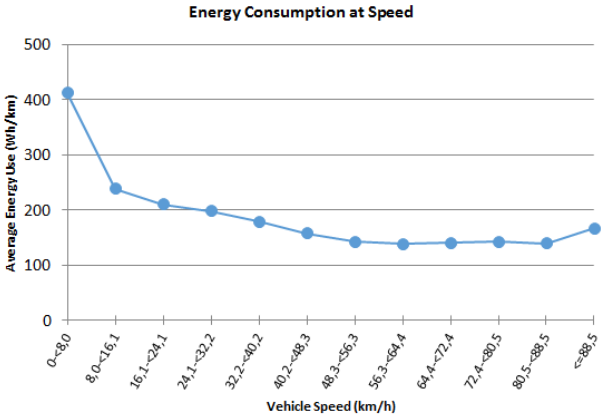

Fig. 2. Nissan Leaf energy consumption at different speeds.

midnight. Except a peak in the morning, for the rest of the day the traffic density remains fairly stable, about 230 vehicles per hour. The major differences between daily flow and weekends are basically a drastic reduction in the morning peak, a slight decrease throughout the afternoon and a small increase overnight.

At the traffic sensor position, the speed limit is 100 km/h. Thus, the speed records are under this limit, from 98 km/h in the midnight to a lower speed of 83 km/h in the morning, being the average speed of 89 km/h. The speed changes between weekdays and weekends are not significant. The rain can slow down from 5 to 10 km/h.

There is a large percentage of light vehicles, with a minimum of 73% at noon. The rest of the day, the composition is around the average of 90%. Overnight, the whole traffic is light vehicles.

B. *Energy Transfered by the DWPT to the EV*

The energy received by the EV depends on the time during which the DPWT system is transferring energy (t_{tr}). This time depends on the numbers and length of the coils, and the EV speed.

$$D_s = D_c \cdot N_c + (N_c - 1) \cdot D_g + D_i \qquad (1)$$

where D_c and D_g are the coil and gap lengths, N_c is the number of coil per segment, D_i is the distance between segments, and D_s is the total segment length. Thus, the length of the proposed segment is 39 meters. As the stretch is 7.3-kilometre-long, the total number of segments (N_s) is 187.

$$t_{tr} = N_s \cdot N_c \cdot D_c / v_{ev} \qquad (2)$$

where v_{ev} is the average speed every hour, taken from Table I.

Thus, the energy received by the EV (E_{tr}) can be easily obtained as follows:

$$E_{tr} = P_{ev} \cdot t_{tr} \qquad (3)$$

where P_{ev} is the power transferred by the DPWT to the EV.

C. *Energy Stored by the EV Battery*

A portion of the energy transferred by the DWPT system is used to supply the EV motors, and the rest is stored in the battery.

The energy consumed by the EV per km (E_{cons}), at different speeds, is shown in Fig. 2. Taking into account this energy and the energy received by the EV, the energy stored in the battery (E_{str}) can be calculated as:

$$E_{str} = \eta_{ch} \cdot (E_{tr} - E_{cons} \cdot L_{sct}) \qquad (4)$$

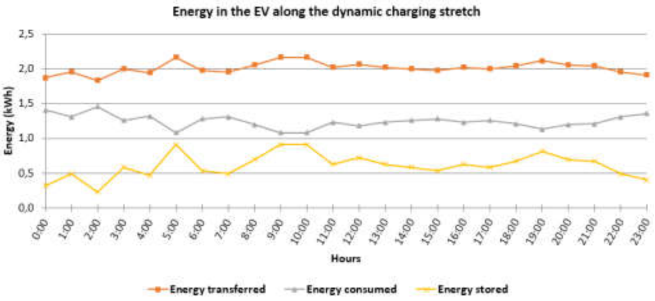

Fig. 3. Average energy transferred to the EV, consumed by the EV, and stored in the EV battery at different hours.

where L_{sct} is the length of the section in km, and η_{ch} is the battery charging efficiency.

Fig. 3 shows the energy transferred to the EV, consumed by the EV and stored in the EV battery along the charging stretch. As can be seen, the higher vehicle speed, the greater the energy consumption increases. On the contrary, the time the vehicle is over the coils and the energy transferred decreases, and so the energy storage decreases.

Thus, the average energy transferred and consumed depend on the speed. In fact, the more the vehicle speed increases, the more energy transferred and consumed decrease, and therefore, the lower the energy stored in the battery is. The energy stored in the battery of an EV is shown in Fig. 4. This energy is clearly dependent on the vehicle speed. A speed of 92 km/h causes an energy storage of 2.05%, while one of 83 km/h causes a storage of 3.80%, therefore, a speed reduction of 9.8% causes a storage increase of 85.4%. These results confirm that the vehicle speed plays an important role in the dynamic charging of EV.

$\alpha + \beta = \chi$. (1) (1)

D. *Power Required by the Entire DWPT System*

The power required by the DWPT system depends on the energy provided to the EV and the efficiency of the transfer system. The different elements involved in the power transfer are: the pickup HF converter installed in the EV, the inductive coupling between two coils, the HF inverter on primary coil and the level adapter converter. The input/output ratio provides an overall efficiency (η_{tr}) of 73% [16]. Therefore, the energy required by the DWPT system at an hour (E_{DWPT}), and therefore, the power required by the DWPT (P_{DWPT}) and

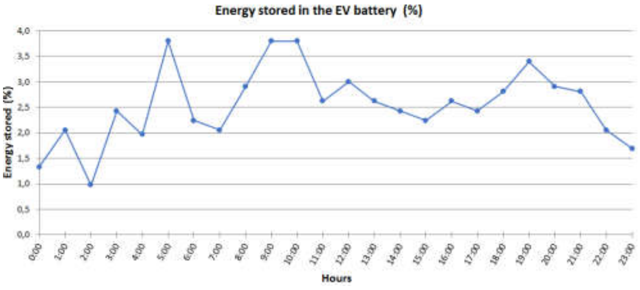

Fig. 4. Energy stored in the EV battery at different hours.

provided by the grid (at 1.5 kV MVDC) can be obtained by:

$$P_{DWPT} = E_{DWPT} = \left(\frac{E_{tr}}{\eta_{tr}} \cdot N_{vh} \right) \cdot I_{lht} \cdot I_{ev} \tag{5}$$

where N_{vh} is the traffic density per hour, I_{lht} and I_{ev} are the per unity value of light EV in the charging stretch and EV penetration rate, respectively.

The power required by the entire DWPT system is shown in Fig. 5. Obviously, the power demand is closely related to the traffic. The higher traffic density, the greater power required. In addition, the vehicle speed plays a main role, because it defines the residence time on the coils.

The penetration rates of the EV play another important role in the profile of power required by the entire DWPT system. If the IEA prospects are right [3], most of vehicles at the end of this century will be EV and can be assumed that a lot of them will be equipped with DWPT systems. However, currently, this is an additional mayor source of uncertainty. For this reason, Fig. 5 depicts three different penetration rates: the utopic one, considering that all the vehicles will be EV and equipped with DWPT system, a low rate of 25% and a medium rate of 50%. As can be seen, penetration rates can smooth power peaks and level excursions, with significantly reducing values.

V. CONCLUSIONS

This paper presents a dynamic wireless power transfer system for charging EV in a single lane of 7.3-kilometre-long stretch of the A-381 Highway in Cádiz (Spain). The study focuses on determining the power and energy requirements, throughout a representative weekday and considering a typical EV light car (Nissan Leaf). The main assumption is that the DWPT system is not only a battery charger, but it allows supplying the motors, charging the battery, and therefore, increasing the vehicle autonomy.

The analysis of the energy transferred to the EV and the energy stored in the battery shows that these energies are closely related with the vehicle speed, assuming that up to 40 kW is transferred to the coil and the power that is not consumed by the vehicle is used to charge the battery. In fact, if the EV considered in this study is moving to a speed of 92 km/h, the energy stored in the battery increases at 2.05%, whereas the speed is of 83 km/h, the energy storage increases at 3.80%.

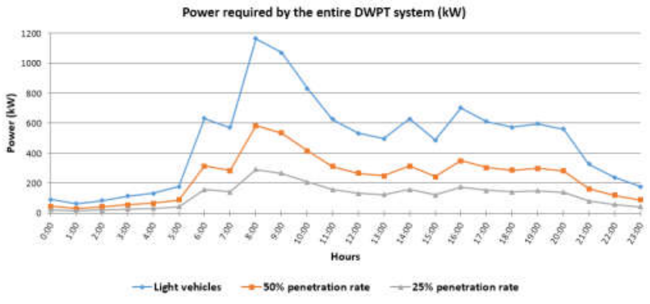

Fig. 5. Power required by the entire DWPT system.

In the case study, the maximum power required by the entire DWPT is 1164 kW (291 kW) for a penetration rate of 100% light EV (25%), with a traffic flow of 460 vehicles per hour at an average speed of 87.5 km/h.

In conclusion, it is seen a great variability in the power and energy requirements and great dependency between the power and energy demand and the traffic, not only the traffic density, but the number of light EV in the traffic composition and the penetration rates of EV.

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