On the energy efficiency of quick DC vehicle battery charging

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Abstract

Paper deals with an extensive experimental activity carried out in Italy by ENEA Research Lab on Low impact vehicles and by the Energy engineering group of the University of L'Aquila about the energy efficiency of quick vehicle battery charging using a DC CHAdeMO compliant recharging 50 kW infrastructure. Both the charger and the vehicle (a Nissan Leaf) battery were fully monitored to gather detailed information about their behaviour at different power loads. The performances of the battery pack equipping the vehicle have also been monitored and evaluated through an extensive campaign, both on typical urban and extra-urban uses, and on vehicle rolling test bench.

Keywords: Energy efficiency, Fast Charging, DC CHAdeMO standard

1 Introduction

Generally speaking [1], potentiality of electricity as fuel for transportation purposes is huge, since it could:

• decrease the EU's oil dependence, as electricity is a widely-available energy vector that is produced all over the EU from several primary energy sources (including renewable and nuclear);

• decrease the CO2 emissions of the transport sector, especially if the expected continuing increase in the share of renewable energy sources in the EU power generation mix is considered;

• provide for innovative electric vehicle solutions removing design constraints based on traditional internal combustion engines, so leading to lighter and more efficient vehicles.

Anyway, the logistic issues for vehicle charging management will be a key issue for the power system optimisation: a smart use of on-board batteries could be used to widen and optimize the integration of renewable electricity on the electric grid.

Local emission of pollutants from transport is completely suppressed when using electricity for propulsion. Electrical vehicles therefore are ideally suited for densely populated urban areas, which still have difficulties to meet air quality obligations.

Limiting the attention on road vehicles, electric propulsion may use a number of different technologies, also including hybrid configurations (using a combination of an ICE and an electric motor) [2-8], and/or alternative fuels, both based on renewable or fossil sources [9-12].

Authors gained a huge experience on all these possible alternative solutions and still are convinced that electric vehicles (EV) are certainly the most effective solution in a mid-term future urban mobility scenario.

All the other options, in fact, may be considered both as bridge technologies towards full electric application (to be used in urban environment) and as a long-term solutions for wider range vehicles (for suburban and highway applications). Hybrid electric vehicles (HEV) without the external charging possibilities do not contribute to oil substitution. They can, however, save oil and reduce CO2 emissions by improving the overall energy efficiency of a vehicle.

Only rechargeable vehicles in their various forms (Pug-in hybrids, PHEV; Plug-in range extenders, PREV, and full electric battery based solutions, BEV) offer routes to oil substitution and full decarbonisation. Battery technologies currently seem to be a short-mid-term solution for sustainable mobility, while fuel cell Hydrogen based propulsion (which is treated on another TRS) still seems to be a long term electric-propulsion based technology. One of the key issues in the introduction of electric propulsion in urban contexts concerns the energy density and efficiency, together with the reliability and cost of the possible on-board electric storage technologies.

If the attention is moved from on-road urban transport to other transport uses, continuous or frequent discontinuous external electricity supply may be considered as an option (with limited or absent electric storage on-board). This is the most common option for railways in all forms (tram, metro, passenger train, freight train), but may become a reference also for urban buses in a near future, using high power fast recharging infrastructures, both requiring (trolley-based) and not-requiring (induction-based) the contact between the vehicles and the charging equipment.

2 Quick charging devices

Quick vehicle charging could be an efficient solution to enhance vehicle mileage and to decrease on-board storage capacity and weight.

Anyway, the efficiency of fast recharging will play a crucial role in its diffusion, All the energy losses introduced, in fact, must be taken into account both in terms of carbon dioxide emissions, and in terms of batteries stress (lifecycle duration).

There are two possible configurations for quick chargers: the first is based on on-board AC/DC conversion (AC chargers); the second on DC vehicle power supply. In this latter option, further advantages are connected to vehicle weight reduction, but complexity is increased for the need of vehicle to grid communication: charging operation is controlled by the off-board charging device, which has to communicate with the on-board BMS (Battery Management System).

The International Standard IEC 61851-1 names the first option ”Mode 3”: the EV is connected directly to the AC supply network using an electric vehicle supply equipment (EVSE); a pilot control circuit is implemented to perform some safety controls, permitting to verify that the connector is properly inserted in vehicle inlet, to test the continuity of earth circuit and to provide power switch-off without halting the control circuit (in case of pilot circuit failure).

Second option is, instead, referred as ”Mode 4” in IEC 61851-1: the EV is connected to the power source through an off-board AC/DC converter and battery charger ; “pilot” functionalities are enabled also for mode 4. A serial data communication line is needed to allow the BMS to control the off-board charger.

Interoperability of EVs is a major challenge, joining EVs and charging station manufacturers, as well as international standardization authorities. Waiting for the harmonization of connectors, as well as of communication protocols, various DC quick chargers topologies are today adopted.

Among those, Nissan and Mitsubishi are using CHAdeMO protocol, while BMW and Volkwagen are adopting the SAE J1772 combined charging system (CCS). Tesla motor use a super-charger based on own connector and useful only for Tesla vehicles. Finally Chinese market is emerging with an own product. Each of these standards operate at a variety of DC voltages and each has a different maximum power level.

Japanese automakers started developing CHAdeMO standard in the mid-2000s: the standard is now widely diffused with more than 5,200 charging stations installed around the world (1,532 in Europe) [13]. Lately CHAdeMO protocol was acknowledged as European standard and made it one of the two quick charging standards designated by European standardization committee [13].

CHAdeMO imposes a DC output maximum power of 62.5 kW (under a voltage up to 500 V and a current up to 125 A), with a standard 10 pins power connector (reported in Figure 1). Two pins are dedicated to DC power lines and two are used for digital communication (CAN bus). The remaining six lines are dedicated to start/stop charging, connection check and charge enabling (figure 2).

Figure 1: 10 pins CHAdeMO connector

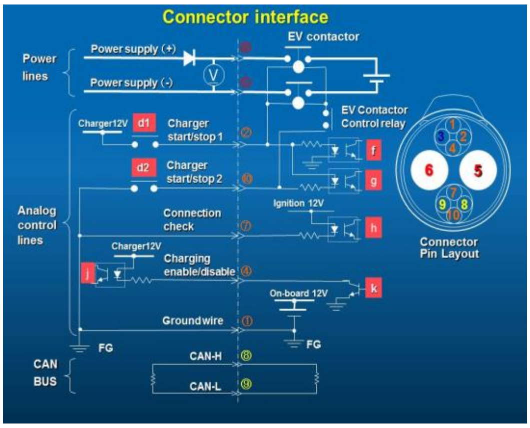

Figure 2: CHAdeMO interface

Figure 3: Nissan Leaf charging socket

3 Aim of experimentation

The main obstacles to the full-scale EV diffusion are related to the electric storage limits both in energy and in power. A higher specific energy of electric storage may extend operative range of the EV, while higher specific power increases driving performances. Moreover, battery have a limited number of complete charge/discharge cycles, after which they show substantial deterioration in in nominal capacity: to extend batteries lifetime, the tendency is to use partial charge/discharge battery cycles.

Life time of electric storage is an important issue in EV especially for the high cost of Li-ion battery in comparison with the total cost of EV. Generally speaking, batteries show a longer life expectancy if limited currents are flowing through both in discharging, and in charging phases: charging a cell at high current rate (e.g. 3C, a current which is 3 times cell nominal capacity) may lead at a premature ageing of electric storage. This ageing can be reflected in a lower battery capacity.

However, some authors [14] didn't experimentally verify this behaviour: quick charging produced only a 5% reduction in batteries lifetime (comparing to slow charging operation), while the decrease in batteries capacity seemed mainly dependent on vehicle mileage.

Quick charging may also lead to lower charging efficiency, as a result of chemical and Joule losses. Reduced efficiency in battery charging, on its, turn, produces increased energy consumption and consistent in energy cost. Further energy losses are also connected to reduced efficiency of high-size transmission lines and power transformers used to supply quicker charger systems.

Taking the lead by these considerations, the present work was aimed at testing the efficiency of battery charging at different power rate and to evaluate the efficiency referred to AC power supply. A quick charger 50 kW CHAdeMO compliant charger was tested on a Nissan Leaf test vehicle.

Nissan Leaf is equipped with a laminated Li-ion battery of 24 kWh of nominal energy capacity and charge capacity of 66 Ah. The nominal voltage is 364 V with a maximum of 403 V. Quick charger station was a EQC-50 model of Circuitor SA powered by three-phase low voltage network (400 V) with a power rating of 77 kVA. DC output power is compliant with CHAdeMO rating (62.5 kW at 125A,500V) while an alternative power output is available for 22 kW AC at 32 A.

Vehicle battery is chargeable both quickly and slowly (figure 3). In slow-charging mode, the maximum power drained is 3.3 kW (the operation is done through on-board charger) and the full charge is completed in 8 hours (domestic charge). In quick mode the CHAdeMO charging system allows a complete charge up 80% of SOC in half an hour.

4 Experimental setup

Nissan Leaf was equipped with an in vehicle Advantech Trek 550 embedded computer designed to meet the needs of fleet management. It is suitable to withstand vibration and electromagnetic noise. It supports transportation protocols as SAE J1939 and OBD-II, as well as broadcast communication.

Figure 4: Advantech Trek 550 embedded PC

The On-board system was used to record both the electric data (battery voltage and current, SOC, energy and power of vehicle battery) and kinematic data (speed and GPS data) of the EV. On-board data were carried out by the in-vehicle CAN bus.

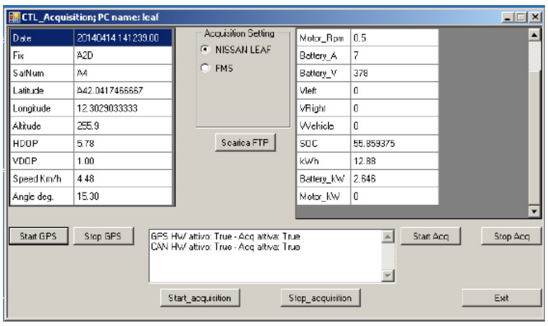

Figure 5: On-board GUI for data acquisition

To complete the measurement chain an automatic measurement system was used to log the battery charger. This system was developed by ENEA and University of L'Aquila to evaluate power converter performance with high accuracy (Figure 6). Data acquisition and conditioning is realised by LabVIEW, processing data coming out from high precision and high speed voltage and current sensors via a NI 6255 board.

Figure 6: LEM DC output sensors

A PC based application has been used to set the quick charging DC power output by limiting the output current.

Figure 7: charging station and meas. system

Two sets of maximum charging power and initial battery SOC were selected in order to test the battery charging efficiency (Table 1) at different power level and initial SOC.

Power output levels were selected on the basis of practical reasons: 50 kW is the maximum output power of quick charger station; 43 kW is the “fast AC” power output on European standard; 22 kW is the three phase power for AC on-board charger; 16 kW is a contractual power for the main electric distributor in Italy; 3 kW is the slow charger power drained from the mains.

P [kW]	16	22	43	50	3
SOC %	20		40		60

Table 1: Power-SOC experimental matrix

Testing vehicle was discharged on-road on different extra-urban routes without significant grade. To complete the investigation a limited set of test were carried out on the roller bench in ENEA Casaccia facilities (Figure 7). In these latter tests, a hard driving cycle copying a real route was adopted with climbs of 6% and three speed levels:40, 50 and 60 km/h.

Figure 7: vehicle testing at roller bench

5 Results

Firstly, a measurement campaign was set up to verify the precision and compliancy of on-board logged data with the more accurate off-board data.

The difference in battery voltage proved to be negligible (< 0.5%) while battery current showed a maximum difference of 6% at low current values (probably due to limited A/D conversion bit number of the on-board data).

CHAdeMO protocol charges the battery using a master-slave configuration (battery being the “master” and charger the “slave”). Every 100 ms, battery gives charger info about required charging current. The charging profile used is a 2-phases constant current - constant voltage profile, as defined by the OEM. Constant current phase duration depends on initial SOC and on charging power, and lasts longer at low SOC and low charging power.

Slow charging was performed at constant current for 8 hours by the on-board charger.

Coulombic efficiency of Li-ion batteries is particularly close to 1, so that its energy efficiency, defined as the ratio between discharging and charging energies, is mainly defined by battery Joule losses. Energy efficiency calculations were made integrating power during battery charging and discharging modes.

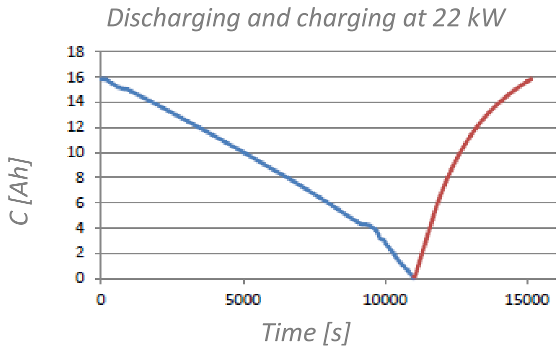

Figure 8: discharging and charging test at 22 kW

Table 2 shows the results of this evaluations as function of charging power.

P [kW]	3	16	22	43	50
Battery η	97.2	97.1	97.0	91.8	94.2

Table 2: Battery efficiency vs. charging power

Figure 9 shows the instantaneous conversion efficiency of quick charger as function of instantaneous output power as resulting from measurements.

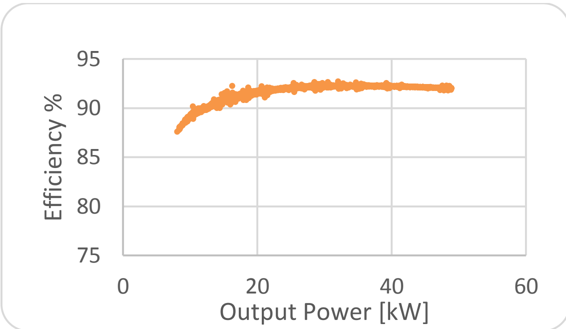

Figure 9: efficiency vs cahrger output power

As expected, the conversion efficiency is decreasing at low power. Data relative to the overall performance of the charger during the charging tests are reported in Table 3.

P [kW]	3	16	22	43	50
Charger η	86	91.6	92.2	92.6	92.6

Table 3: Charger efficiency vs. charging power

The overall efficiency can be calculated multiplying charger efficiency by battery efficiency (Table 4).

P [kW]	3	16	22	43	50
Overall η	83.6	88.5.	89.5	85.0	87.2

Table 4: Overall charging efficiency

The average charger efficiency is depending also on the initial battery SOC, because, as explained, the constant current charging phase lasts longer and high power is sustained for a more relevant part of the charging profile. This behaviour may be highlighted by experimental data, reported in the following Tables 5 and 6, showing efficiency values variations depending on the initial battery SOC.

Charger Efficiency

	P [kW]	3	16	22	43	50
SOC	23	85.0	84.6	91.1	91.7	91.4
	43	85.0	88.1	90.5	90.6	89.7
	60	85.0	83,2	83.7	87.5	83.18

Table 5: Charger η vs power and initial SOC

Charger Efficiency

	P [kW]	3	16	22	43	50
SOC	23	83	82	88	84	86
	43	83	86	88	83	84
	60	83	81	81	80	78

Table 6: Overall η vs power and initial SOC

6 Conclusions

In this paper, the authors presented some preliminary results of an extensive experimental activity carried out in Italy by ENEA Research Lab on Low impact vehicles and by the Energy engineering group of the University of L'Aquila about the energy efficiency of quick vehicle battery charging using a DC CHAdeMO compliant recharging 50 kW infrastructure.

Both the charger and the vehicle (a Nissan Leaf) battery were fully monitored to gather detailed information about their behaviour at different power loads.

The performances of the battery pack equipping the vehicle have also been monitored and evaluated through an extensive campaign, both on typical urban and extra-urban uses, and on vehicle rolling test bench.

Results show the dependency of charger and battery efficiency on charging power and on the battery SOC initial state.

A wider experimental campaign is now undertaking to better control battery discharging behaviour (trough well repeatable quasi-steady vehicle rolling test bench phases) so permitting to better isolate and evaluate the influence of charging power and charging profiles on the overall battery efficiency.

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