Optimization of Electric Vehicle Charging Stations with Battery based Energy Storage Systems using a Pulse Charging Mechanism

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Abstract—The All-Electric Vehicle (EV), whose power is de- rived from a battery with high energy/power density, has become a major contributor to the concept of sustainable development. An EV charging station should be able to deliver the power demanded by a car battery at a given rate. However, as the number of cars plugged in at the station increases, the charging station eventually becomes saturated as it approaches its own output power capacity due to grid limitations. One way to overcome this issue is to integrate a battery based energy storage system to the charging station. However, charging of these storage batteries is again limited by the grid constraints on maximum power and current ratings. As a solution, this work proposes a charging station configuration which uses pulse charging to speed up the charging process of the battery storage while adhering to grid restrictions, especially for level-2 charging stations in Sri Lanka. Furthermore, conceptually, the proposed system can be extended to accelerate the charging process of the EV's battery itself. Experimental results, using a Pb-acid battery, are presented to validate the reduction of charging time due to pulse charging: the results show a 13.5% reduction in overall charging time.

Key words—Electric vehicle, Energy storage, Fast charging, Level-2 charger, Pulse charging

I. INTRODUCTION

As creatures with a consciousness, if one seeks technical development, it should be of the sustainable nature. The electrical engineers have the necessary tools to realize this sustainability in answering world's demand for energy and power. Ground transportation is one of the critical links that defines the quality of the development of a country. With the emergence of concepts of sustainability and environmental awareness, Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and All-Electric Vehicles (EVs) have become important: in fact, in the current market, the latter two have become dominant surpassing the former [1].

With the increasing number of EVs on the road, fast and efficient charging of the their batteries is essential [2]. With the technological advancement of battery technologies, EVs are now equipped with batteries with high energy/power densities; Li-ion batteries for instance [3]. However, the electric capacity of the vehicle is still inferior to the conventional fuel based vehicle: for instance, Nisan LEAF and Tesla Model S have electric ranges of 84 miles and 265 miles respectively [1]. Evidently, this is a matter of further enhancing battery capacities and increasing the vehicle performance. Apart from the limitations in the car side, the charging stations are facing two major difficulties:

1) Power limitations on the grid side [4], [5].
2) Limitations in the speed of charging high-energy density batteries of the EVs [6]–[8].

A typical charging station without energy storage is shown in Fig. 1. Due to grid restrictions, both public and domestic charging stations have limits on how much power and current they can support [9]. For instance, the out of town installation of the commercial "Vega eStation" charging station of chargeNET of Sri Lanka is limited to a current of 60 A from the grid [10]. This is a major problem when more than two EVs need to be charged simultaneously. One way to overcome this problem is to equip the charging stations with energy storage units such as batteries and ultra-capacitors, or integrate renewable sources such as Photovoltaic (PV) panels [11]. One commercial product that enhances this storage capacity is the "UltraBattery" [12]. However, the battery storage itself needs to be charged from the grid, preferably in the night time. The number of storage batteries can be increased to accommodate charging of more vehicles during daytime; however, charging of the storage batteries is again limited due to grid constraints, and duration of a night would eventually become insufficient to fully charge the storage for the usage in the next day.

As a solution, this work proposes a speed-up mechanism that uses current pulse based charging scheme to fast charge the storage batteries during the night time [7]. Note that, with pulse charging, as discussed in the following sections, the required power capacity is the same as the conventional charging. The idea is to increase the number of storage batteries that could be charged in a given time without adversely affecting the lifetime of the battery under the same grid constraints. Furthermore, it is shown that with proper adjustments to the charging rules

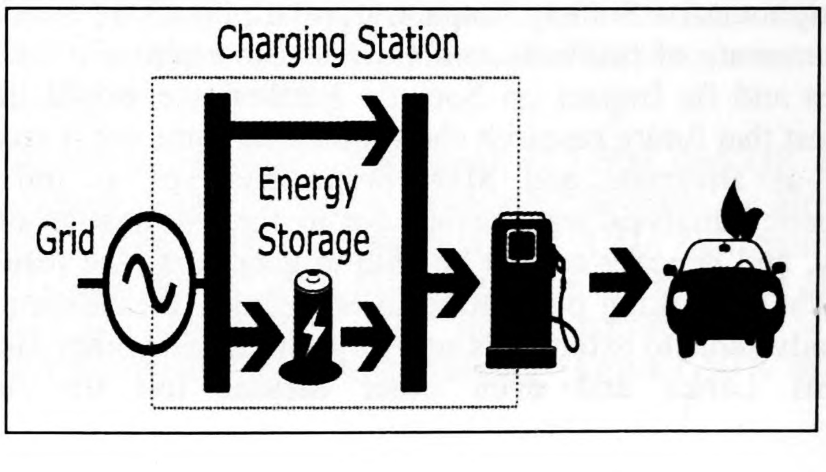

Fig. 1. Typical electric vehicle charging setup without energy storage

TABLE I
EV CHARGING TECHNOLOGIES [11], [13]

Charging Method	Input Voltage (V)	Maximum Charging Current and Optimum Power	Standard
AC level-1	ac 120	16 A /1.92 kW	SAE J1772
AC level-2	ac 208 − 240	80 A /19.2 kW	SAE J1772
DC fast charging	ac 208 − 480 (3 − φ)	200 A/50 kW	CHAdeM

commercial charging technologies for EVs, the pulse charging could be extended to charge the battery in the EV itself, reducing its charging time: this would, increase the number of EVs that could be charged for a given time and a given station power capacity. The reduced charging times for pulse charging is confirmed with experimental results that compare charging times of conventional and pulse charging methods for a Pb-acid battery.

II. ELECTRIC VEHICLE CHARGING STATION REQUIREMENTS AND LIMITATIONS

TABLE I tabulates the major EV charging technologies with their standards and ratings used in the current market. For example, in Sri Lanka, chargeNET associated with Vega Technologies currently supports level-2 charging with 220 V and 15 □ 30 A [10], [14]. And with a 60 A limit on the grid side, only two EVs can be charged at a given time using two of these chargers at a given station at reduced power levels (the maximum charging current of 80 A is not approachable). If the station goes beyond this limit, the increase in tariff in substantial; and, imposing the very high extra cost on the customer is not practicable. This also has a high negative impact on the grid performance as well [15]. With the aid of local battery based energy storage systems, the grid fluctuations could be minimized while providing the necessary load power demand [4]. For instance, a 19:2 kW level-2 charger of 80 A, can be supported by the grid (providing 60 A _ 240 V = 14:4 kW), if an additional power of 4:8 kW is provided by the local storage. It should noted that the local storage should be capable of delivering both energy (to support the minimum time duration to fully charge the battery) and power (to provide instantaneous energy support to work with the grid) in sufficient amounts to achieve this. However, above realizations were made assuming that battery storage units are independent sources. In practice, these batteries need to recharge themselves from the grid, preferably in the off-peak periods the night time. And, now at this situation, the same 60 A limit is faced by the charging station to charge its storage units. However, with 10 - 12 hours of charging time, several battery units could be charged even with grid limitations. Note that, increasing the capacity of the storage is again limited by the number of hours the station has during off-peak time. Therefore, solutions should be found to somehow increase the storage capacity of the station without over compromising grid constraints

III. . PROPOSED METHOD

Optimizing EV Charging Stations Equipped with Battery Based Energy Storage Using Pulse Charging

The overall configuration of the proposed charging station is illustrated in Fig. 2. The system can be used as an ac level-2 charging station, where the secondary converter incorporates an inverter; or a dc fast charging station, where the secondary converter is dc-dc converter.

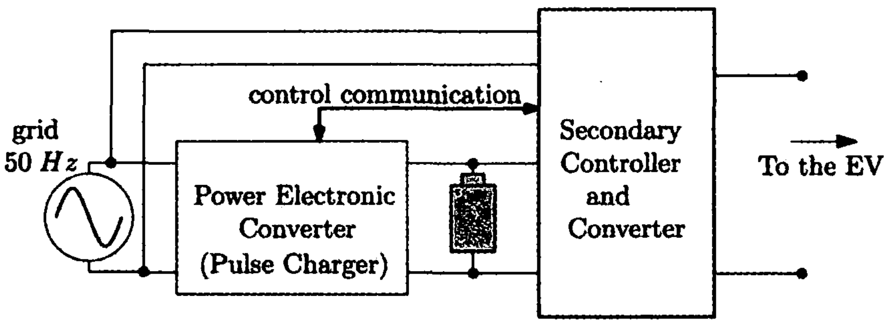

Fig. 2. Proposed charging station setup

The primary power electronic converter is a specially controlled unit to generate pulsed currents to fast charge the storage battery, in most cases a Li-ion battery. The pulse charging circuitry can be realized using a dc link converter with an inductor as a current source as described in [7] and [16]. This converter has the full controllability of the battery; and, also is responsible for the safe operation of the battery. However, the charging mode becomes active only when the secondary controller takes a decision based on load and grid conditions. The secondary controller and converter only sees the battery as a dc power source.

The secondary controller monitors the load demand (i.e. how many EVs are connected to be charged) and utilizes the power input from the grid and the battery storage. Furthermore, when the load demand is lower than the grid maximum power limit, the station switches to a mode where the load power is 100 % supplied by the grid. In this instance, the secondary controller signals the primary converter to charge the storage battery using the remaining grid power. The two states of the system can be summarized as follows:

1) Pload > Pgrid□max: storage battery discharges providing power to the increased load demand

Pload = Pgrid + Pstorage ---------------(1)

2) Pload < Pgrid□max: storage battery gets charged from the grid while the grid fully supports the load demand

Pgrid = Pload + Pstorage ----------------(2)

It can be seen that, at night time, when the load is zero, the grid power is fully utilized to charge the storage using the pulse charger: Pgrid = Pstorage.

Note that, the pulse charger draws the same average current from the grid as the conventional charger [7]. However, as discussed in the experimental section, due to the pulsed nature of the current fed into the batteries, the battery chemistry allows the batteries to be charged at a reduced time for the same average current. Assume that the gain in time with pulse charging is tp % of the conventional charging time for the same average current. Then, the amount of additional battery units (nextra) that can be charged with the proposed method for a 10 hour off-peak time for same grid constraints is:

$$\text{nextra} = 10 \times \frac{\text{tp}}{100} \times n\text{-----------(3)}$$

where n is the number of batteries that could be charged within one hour using conventional charging. Note that the power electronics do not have to double their ratings as the average current is not altered in the proposed method. In fact, the similarly rated power electronics could be utilized by choosing a suitable switching frequency according to the pulsed current rating specifications of the semiconductor switch (generally, the pulsed current rating of a semiconductor switch is around 150 % of its average current rating).

B. Extension to Fast-Charge the Electric Vehicle Battery Itself

A further advantageous extension of the proposed charging station setup could be realized: an additional pulse charger could be used as the secondary converter with necessary topological and control modifications to charge the EV battery directly. However, the nature of the current and voltage pattern output of the pulse charger is not compatible with existing charging technologies. For instance, the on-board charging circuitry for level-2 charging has monitoring circuits that cut off the current path if its specifications are not met: for instance, the peak value of the pulsed current might exceed the specified limit, although the average current is within limits. However, if modifications to the control protocol inside the EV is allowed, such a scheme could be realized.

C. Effect of Pulse Charging on Battery Performance and Battery Lifespan

Studies on Li-ion batteries have observed that the use of a current pulse stream in place of a continuous current stream tend to improve the charging time of the battery: and more importantly, the battery lifespan is also improved [17]–[19]. One reason identified for this phenomenon is the existence of a relaxation time (with zero injected current between two pulses) that allows the chemical processes inside the battery to be stabilized before the next current pulse is injected. Furthermore, this inhibits undesirable chemical reactions that could take place [18] that hinders the charge transfer. The overall effect is that, the charge delivered to the battery in a given time period is increased by a considerable amount [19]:the results are discussed next.

IV. EXPERIMENTAL RESULTS

Experimental results are presented to validate the reduction of the charging time when pulsed charging is adapted instead of conventional charging. The experiments were carried out for a commercial Pb-acid battery of 6 V/4.5 Ah rating. The experimental pulse charging circuit is shown in Fig. 3. A simple open loop control using a dspic30f4011 was used to generate the switching signals for the IGBTs of the pulse charger: this delivers a pre-defined set of pulsed currents to the load for preliminary testing.

Consider Fig. 4 and Fig. 5 which show battery voltage and current variations for the conventional Constant Current (CC) Constant Voltage (CV) methodology and pulse charging methodology respectively. First consider the conventional method: in the CC phase, a current of 400 mA was continuously fed to the battery until its open circuit voltage reached its rated value of 7.3 V . Then, in the CV phase, the open circuit terminal voltage of the battery was maintained at 7.3 V until the average current drawn by the battery dropped to 2% of its rated value. The results show that the total charging time takes around 214 minutes: 70 minutes for the CC phase and, 144 minutes for the CV phase.

Secondly, for pulse charging, after allowing the battery to achieve same initial conditions, a current pulse stream with a frequency of 5 kHz (with 0.5 % duty) was fed to the battery. Note that in the pulse charging methodology, both CC and CV phases are operated using pulsed currents. Although the charging time in CC phase is increased compared to the conventional method, here, the total charging time is reduced to 185 minutes due to the significant reduction in CV phase's charging time.

Therefore, the reduction in the total charging time for pulsed charging in contrast to the conventional charging is $(214 - 185)/214\ \% = 13.5\ \%$. In a system of several battery units, this gain is quite significant. Now, referring back to (3), the additional storage battery units made available for the EV charging station for a 10 hour off-peak time is calculated as,

$$n_{extra} = 10 \times (13.5/100) \times n = 1.35n \qquad (4)$$

Now the total number of batteries that is charged during 10 hours is $10 \times (n + 0.135n) = 11.35n$. With conventional charging only 10n units will be charged.

Note that in the conventional method, the duration of the CC phase is lower compared to the pulsed method (compare Fig. 4 and Fig. 5). However, in the CC phase of the pulsed method, the battery stores charges at a higher rate, despite its increased duration.

This can be verified by ceasing charging of the battery when its terminal voltage reaches its rated value (at the end of the CC phase), and then by discharging the battery using same conditions for the two methods. The results are shown in Fig. 6: the significant increase in the discharge time of the pulse charging method shows that it stores 54.5 % more charge in the CC phase, in contrast to the conventional charging methodology. Note that the increase in CC phase in pulsed method is lower than 50 % in contrast to the conventional method. This signifies the fact that rate of storage accumulation is higher when pulsed currents are fed to the battery.

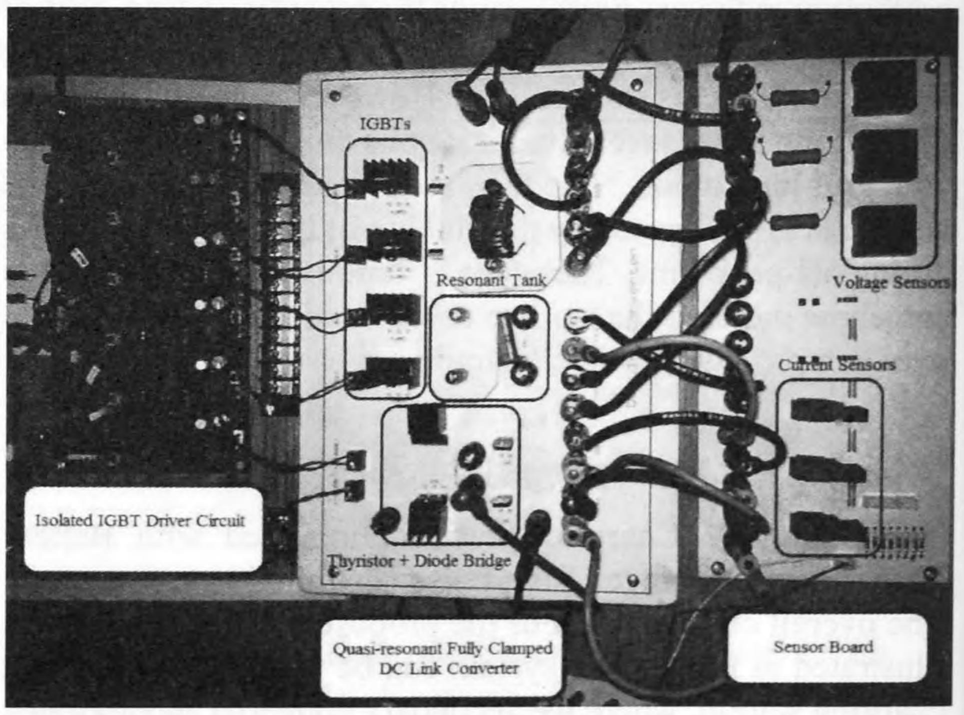

Fig. 3. Experimental setup capable of generating current pulses

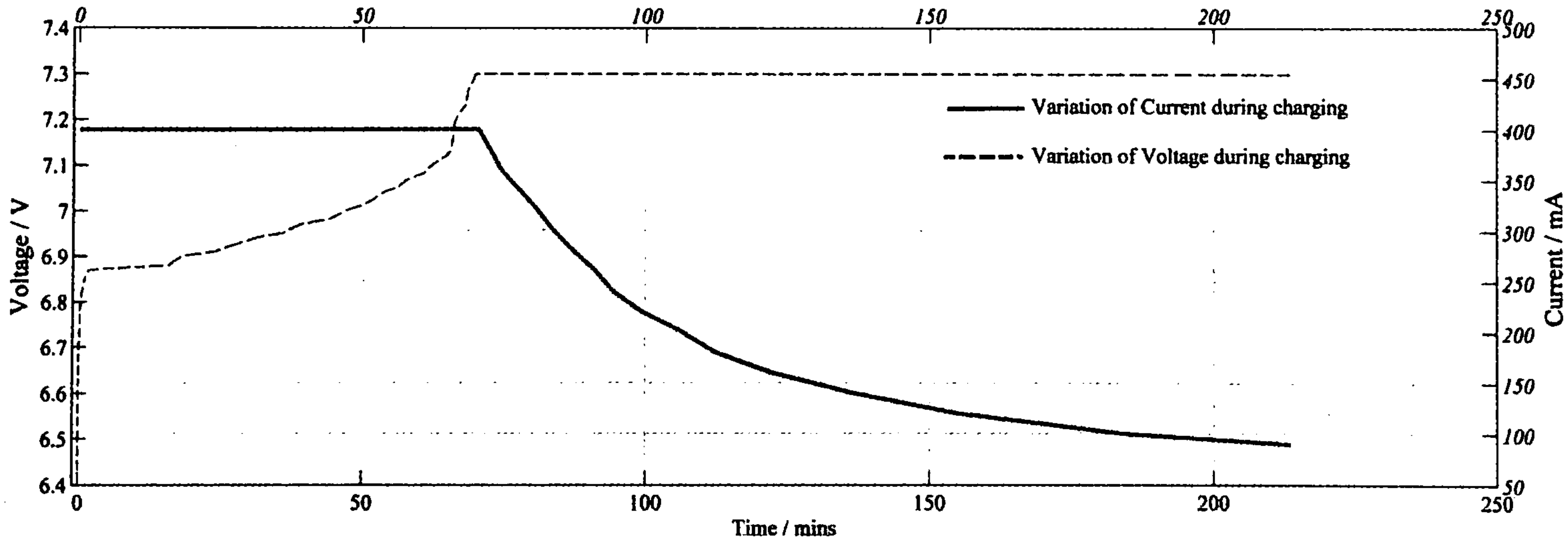

Fig. 4. Voltage and average current curves for conventional method of charging

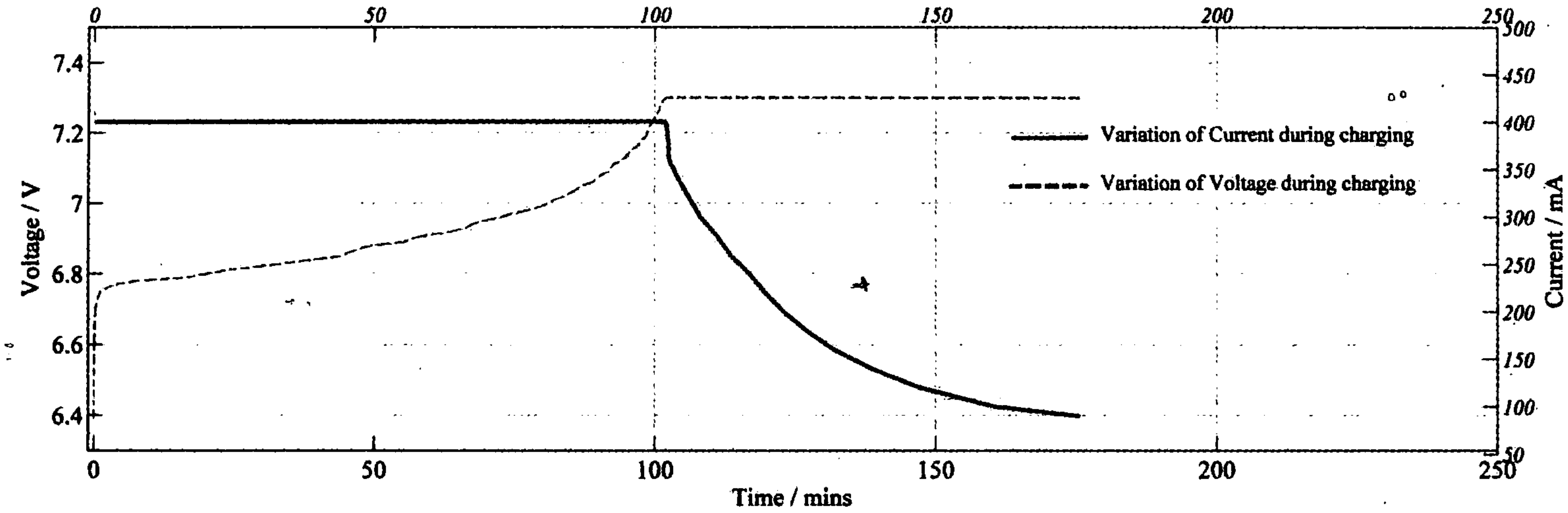

Fig. 5. Voltage and average current curves for pulse charging

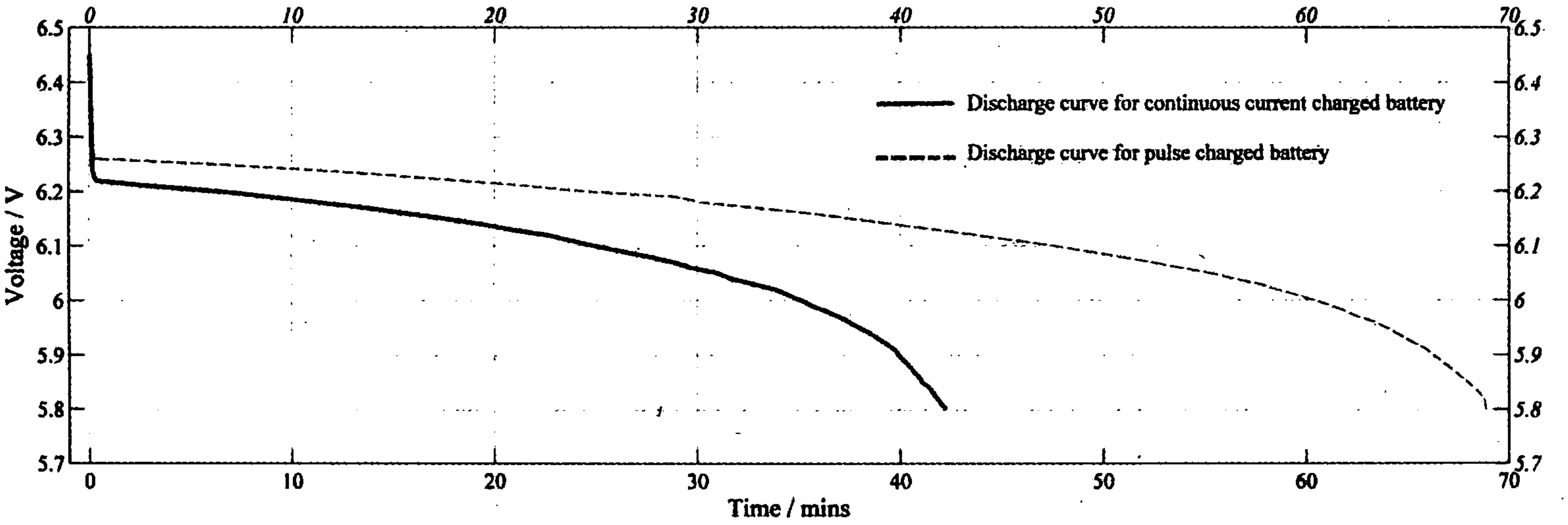

Fig. 6. Comparison of the retained charge in the CC phase for the two charging methods

V. CONCLUSION

A method to increase the overall capacity of EV charging stations subjected to grid current/power restrictions is proposed. The charging station is equipped with battery based energy storage, preferably with Li-ion batteries, to increase the number of EVs that can be charged during peak hours. During off-peak hours, the storage batteries are charged exploiting a pulse charging method, reducing the overall charging time of a given battery while drawing the same average current (and power) that of conventional charging schemes. The idea could be extended to speed-up the charging process of EV's battery itself.

Current pulse based charging offers some interesting advantages over the conventional CC-CV charging process: 1) reduced overall charging time, and 2) improves the lifespan, as well as the performance of Pb-acid and other batteries with similar chemical characteristics. The results obtained for a commercial Pb-acid battery showed that charging time can be improved by 13.5% if pulse charging is employed. Furthermore, pulse charging improves the discharging curves, suggesting that it improves the lifespan of Pb-acid batteries. Similar arguments can be made on Li-ion batteries: however, exact improvement details of Li-ion batteries are to be determined in future extensions of this work. The comparison of retainable charge stored for the two charging methods suggest that the CC phase of the conventional charging method exhibits a pseudo charging characteristic: not all the charges drawn from the input power is stored in the battery. However, pulse charging exhibits a proper charging characteristic in CC phase accumulating more charge into the battery; and therefore, making the CV phase much shorter, and consequently shortening the overall charging period.

The stability of the charging station with integrated pulse charger and Li-ion batteries under various grid conditions needs to be qualitatively analyzed. Moreover, the extension of pulse charging concept to charge the EV battery itself needs further examination on charging technology protocols.

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