

Review and impact of fast charging techniques on batteries and chargers in Electric Vehicles

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Summary

This paper aims to show the impact of different battery fast charging techniques on the Electric Vehicle batteries and the AC/DC and DC/DC converters used in chargers. The AC/DC converter is the three-phase voltage source converter (VSC) and the DC/DC converter is the non-isolated Buck/Boost converter. Different charging techniques used in current Electric Vehicles (EVs) will be simulated, and specific techniques mentioned in the literature and specifically conceived for fast charging are compared to the conventional methods. The impact study includes the voltage and current ratings of the switches, the converters efficiency and the battery performance. The paper will then find a compare these charging techniques and discuss the results.

Keywords: BEV (battery electric vehicle), CHAdeMO, DC-DC, fast charge, lithium battery

1 Introduction

Electric Vehicles (EVs) have been the centre of research for several years now, due to their positive impact on the environment [1]. The main source of energy in these EVs, which is the battery, has seen a lot of progress since the first EV was invented. This progress is not limited to the battery technology itself only, but also the electronic circuit responsible of connecting the battery to the grid for its charging.

The progress made in the power electronics field has allowed the vehicle battery to be charged effectively using appropriate converters in chargers. For example, Fig. 1 shows the general configuration of a battery charger which is comprised of a grid-side AC/DC converter and a battery-side DC/DC converter [2].

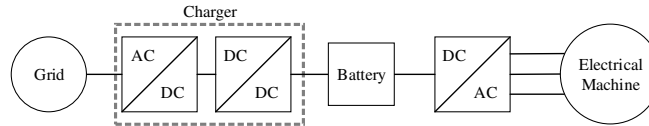


Figure 1: General configuration of a battery charger for EVs

In order to reduce the charging time, researchers are focusing on the conception of EV batteries able to withstand an important charging power. Several standards, such as SAE (Society of Automotive Engineers), ICE (International Electrotechnical Commission), IEEE (Institute of electrical and electronic Engineers) have divided the charging powers into different levels, as seen in Table I, in which the levels are specified according to the SAE J1772 [3].

Table I: Charging power level according to SAE J1772

	Charging voltage (V)	Charging current (A)	Charging power (kW)
AC Level 1	120	16	1.9
AC Level 2	208/240	16-80	Up to 19
AC Level 3	208/240	80	More than 20
DC Level 1	200/450	80	Up to 36
DC Level 2	200/450	200	Up to 45
DC Level 3	200/600	400	More than 45

Fast charging, which is considered to use a power greater than 36 kW, is the process that most of the EV manufacturers are trying to adopt, since that power is able to charge the battery in a reduced time, which will remove an important obstacle behind the EV commercialization.

In addition to specifying the power levels, several standards are trying to set specific requirements considering the charger structure and energy transfer. The most widespread standard is CHAdeMO, since the number of CHAdeMO fast chargers has exceeded 10 000 worldwide [4]. Another widely used standard is the Tesla Supercharger which is currently available for Tesla vehicles.

Despite the fast charging standardization process being developed, the battery charging technique is still in its early stages of research, since the most widely used technique is the CC/CV (Constant Current/Constant Voltage) technique, which will be explained later. This method used for charging Li-Ion batteries using level 1 or 2 power, can still be used in the fast charging process, but becomes largely ineffective and can cause a degradation in the battery characteristics if the fast charging cycles increase [5].

This paper aims to propose a charger structure and state the function of its different components. Several conventional charging techniques will be applied to this charger and their impact will be simulated and compared, such as current and voltage switch stress, overall efficiency, battery SOC (State Of Charge) ... The next section will propose some methods specifically conceived for the fast charging process and will compare them with the conventional techniques.

2 Structure of the charger

The purpose of this section is to propose a structure for the battery charger and briefly describe the functions of its components in order to simulate the different charging methods.

Fig. 2 shows the structure of the battery charger.

The grid-side LCL filter is composed of two inductances L_s and L_F with their internal resistances R_s and R_F respectively.

The AC/DC converter is a three-phase VSC, composed of six switches $T_1, \dots, T_6$, and the DC/DC converter is a bidirectional Buck/Boost composed of two switches T_{DC1} and T_{DC2} . The charger is chosen to be bidirectional, in order to anticipate the bidirectional flow between the battery and the grid [6, 7].

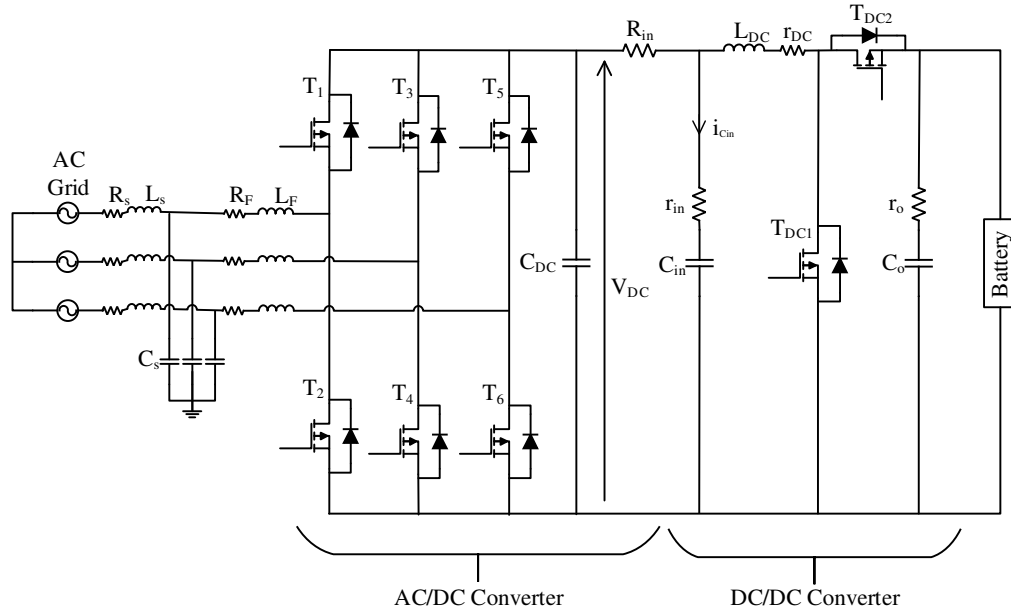


Figure 2: Structure of the EV battery charger

A detailed model of this charger and an appropriate control are proposed in [8], where the bidirectional power flow is verified and the functions of the different components are specified. In fact, the grid-side LCL filter reduces the grid harmonics, and the AC/DC converter maintains the DC bus voltage at a desired value (which is 400 V), ensures a unified power factor between the grid voltage and current, and filters the current harmonics in order to respect the IEEE 519-1992 norm regarding the harmonic distribution and the THD (Total Harmonic Distortion) [9].

The battery-side DC/DC converter charges the battery according to a specified charging technique, and communicates with the BMS (Battery Management System) in order to ensure the safe operation of the battery.

The battery characteristics chosen for this type of application appear in Table II.

Table II: EV Battery characteristics

Nominal voltage	400 V
Maximum voltage	441 V
Minimum voltage	350 V
Energy	23.66 kWh

3 CC/CV charging technique and its variants

Several battery charging techniques have been used for battery charging in different applications [10], but some of them have proven to be the most effective for vehicle applications, and are widely used in today's EVs.

3.1. CC/CV charging

This algorithm allows the battery to be charged by a Constant Current (CC) supplied by the DC/DC converter. The CC charging will result in an increase in the battery voltage, as shown in Fig. 3. The CC stage of the charging process finishes when the battery voltage reaches its maximum allowable value V_{max} . That is when the Constant Voltage (CV) phase begins, where the battery voltage is constant and the battery current decreases until it reaches its cut-off value $I_{cut-off}$.

This widely used technique is safe and allows good control of the electronic circuit connected to the battery. Despite some stability issues related to the switching period between CC and CV, this method guarantees a safe and complete charge of the battery.

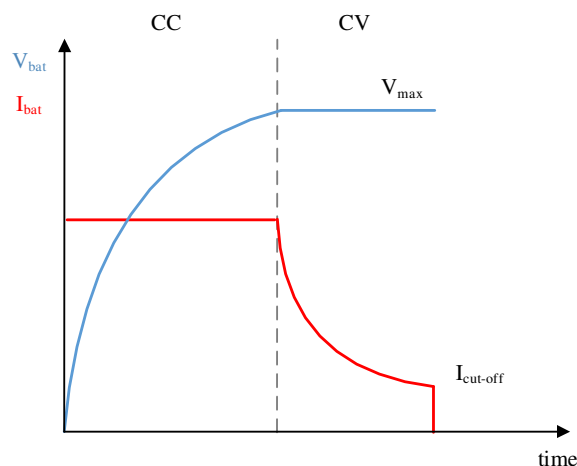


Figure 3: Battery current and voltage during the CC/CV charging technique

3.2. Multi-stage CC charging

A variant of the method stated above is the multistage CC, which is employed in order to increase the battery charging acceptance and decrease the transient effects of the transition between the CC and the CV stages. The evolution of the battery current during the Multi-stage CC charging method appears in Fig. 4 [5].

This method proves to be more suitable for a fast charging application, since a high current is used during the CC stage. The step increase in the charging current reduces the transient effect and helps achieve a smoother transition between CC and CV.

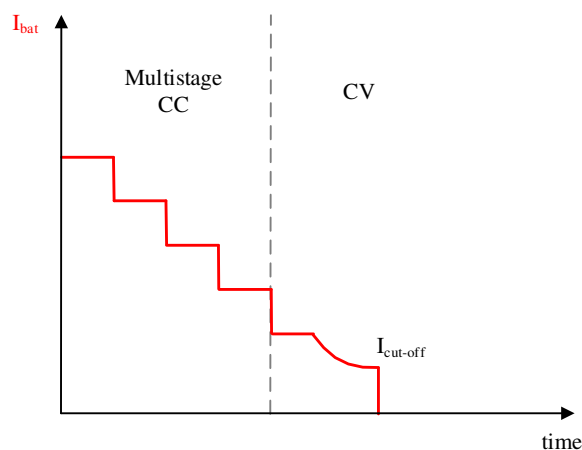


Figure 4: Battery current during the multistage CC/CV charging technique

3.3. Pulse charging

The two methods stated previously are applied for battery charging in different applications, including EVs [11]. However, while the research in progress is focused on increasing the charging power level in order to decrease the battery charging time, these methods begin to create polarization problems especially with very high power levels. Hence, several new techniques are being employed specifically for vehicle applications, such as pulse charging, appearing in Fig. 5.

The idea is to briefly discharge the battery with negative current pulses while charging it, in order to decrease the polarization and the temperature rise [12]. The negative pulses can be applied to either the CC/CV charging (Fig. 5(a)) or the multi-stage CC/CV (Fig. 5(b)).

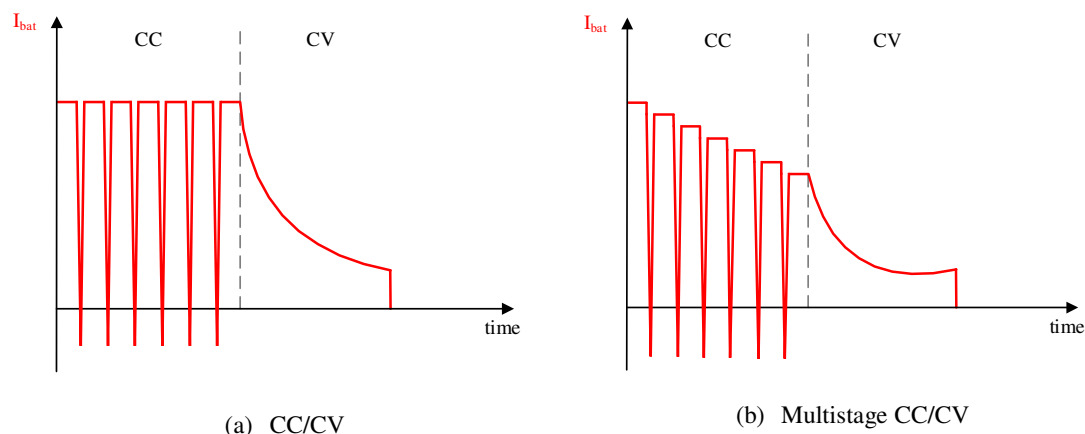


Figure 5: Charging techniques with negative pulses

4 Fast charging techniques

The previous charging techniques result in the battery polarization when the charging current increases [5]. Therefore, several new charging methods are employed in order to reduce the polarization and to increase the charging acceptance.

4.1. SOC based CC/CV charging

The main idea behind the fast charging process is to reduce the charging time. However, the CC/CV charging technique results in a high charge time, due to the fact that the CV stage takes a lot of time because of the current voltage examination. A novel charging method proposed by [11] estimates the battery SOC and switches from the CC to the CV stage when the SOC reaches a maximum value. This results in the extension of the CC stage and the reduction of the CV stage, which is suitable for fast charging.

4.2. Internal resistance assessment

Another parameter which was neglected in the previous charging techniques is the voltage drop due the battery's internal resistance. In fact, with a low charging current this voltage drop can be neglected and the battery is able to be charged with its nominal voltage. However, when the charging current increases, this voltage drop becomes important and fails to be neglected. That is why [13] proposes a CC/CV charging method but with a reference voltage slightly higher than the nominal value, which will result in a decrease in the CC charging time.

4.3. Cell balancing assessment

Another parameter that was neglected during the slow charging is the cell irregularities. In fact, because of the slight differences between each battery cell, some of them will charge faster and when one cell reaches its maximum voltage, the BMS (Battery Management System) will stop the charging operation until it dissipates the excess energy from this cell and then will reconnect the charger again. For a high charging current, the cell imbalances are important and this disconnection will occur more than once, which will compromise the performance and characteristics of the battery.

The proposed charging scheme in [14] takes into account this problem, and switches from the CC to the CV charging once a cell reaches its maximum voltage instead of disconnecting the charger. This way the fully charged cell will be maintained at a constant voltage level and the other cells will continue to charge until they reach their maximum voltage. This way, the charging time will significantly decrease especially with a high charging power and the battery balancing process will continue to operate.

Due to the fact that this method is similar to the CC/CV technique, but adds into account the cell balancing, it will not be simulated, but its advantages will be evaluated later in the paper.

4.4. Positive pulse charging

Ref. [15] dives deep into the chemical processes that happen in the Li-Ion battery when it is being fast charged. In fact, a continuous high charging current can lead to dendrite formation on the anode due to the fact that the ions do not have enough time to move into the electrodes. That is why the proposed charging technique appearing in Fig. 6 shows that the charging current takes the form of positive pulses. In addition to that, the charging starts at a lower rate, in order to counter the voltage drop due to the internal resistance which is high during the first charging stage. During this first stage, the battery is charged by a positive pulsed current until the battery SOC reaches 50%. The second stage begins at a SOC equal to 50% and continues until the SOC reaches 80%. During this stage, a several CC/CV techniques are applied. After that, a decreasing positive pulsed current is then adopted until the SOC reaches 95%, and afterwards a low rate CV stage allows the battery to be fully charged.

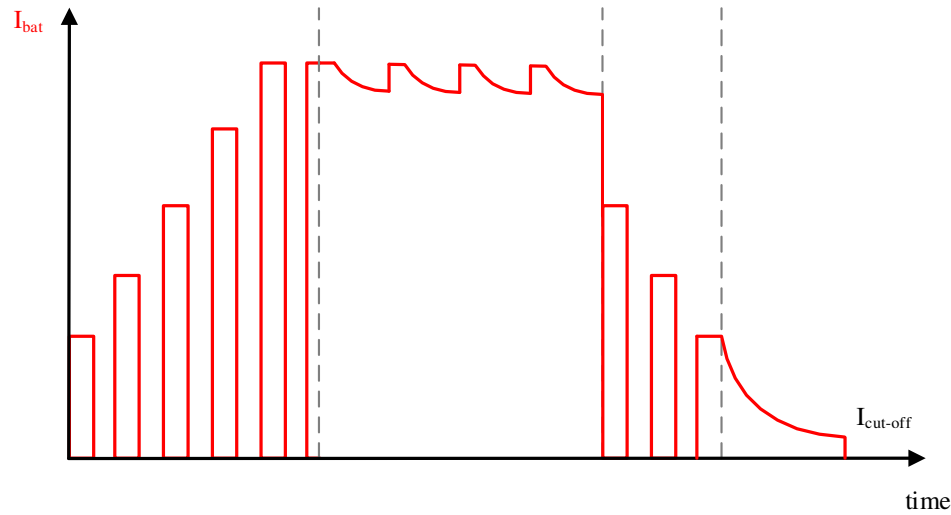


Figure 6: Positive pulse charging

The step-by-step process of this method is mentioned below:

- Step 1: $0 \leq SOC \leq 50$: Increasing positive pulsed current (from 0.5C to 2C)
- Step 2: $50 \leq SOC \leq 80$: Multiple CC/CV charging with a current between 2C and 8C during the CC stage
- Step 3: $80 \leq SOC \leq 95$: Decreasing positive pulsed current (from 2C to 0.5C)
- Step 4: $SOC \geq 95$: CV stage until the current reaches 0.1C to 0.05C

4.5. Variable frequency charging

Ref. [16] proposes an alternative charging current with a variable frequency. A detected sink current is used to estimate the battery charge. When the sink current is smaller than 0.01C, the battery is considered fully charged. When it needs to be charged, the current frequency is adjusted according to the SOC. The experimental results carried in this paper shows a charge time improvement by 25% compared to the CC/CV technique, but it is unclear as to how this method is compared to the other charging methods.

The simulation of this method depends largely on the internal composition of every specific battery, which makes it hard to simulate using Matlab. The results of [16] will be adopted and compared with the rest of the methods.

5 Simulation of the charging techniques

The whole system (grid, charger and battery) is simulated using Matlab/Simulink/SimPowerSystems, and the references for the battery current and voltage are set for every type of charging method. Note that the slight variations that are seen between the current and its reference is largely due to the battery model used in the system, which can be sometimes inaccurate and is unable to fully represent a fast charging process.

Fig. 7 (a) shows the reference battery current for the CC/CV charging technique and the actual current. Note that because of the length of the CV stage, the current in the simulation will decrease at a faster rate than normal, in order to show the effect on the battery.

Substituting the CC current by a stage where the current decreases in steps is represented in Fig. 7 (b) where the multistage CC/CV is represented. The addition of negative pulses to the two methods previously stated is represented in Fig. 7 (c) and (d) respectively.

Estimating the battery SOC and switching from CC to CV according to the SOC value instead of the voltage value represents the SOC estimation method in Fig. 7 (e).

Fig. 7 (f) takes into account the voltage drop caused by the internal resistance and adds the corresponding current to its reference, in order to improve the charging time.

Fig. 8 shows small portions of every step of the positive pulse method. The comparison will concentrate on the final step in order to evaluate the charging time and the effect on the battery.

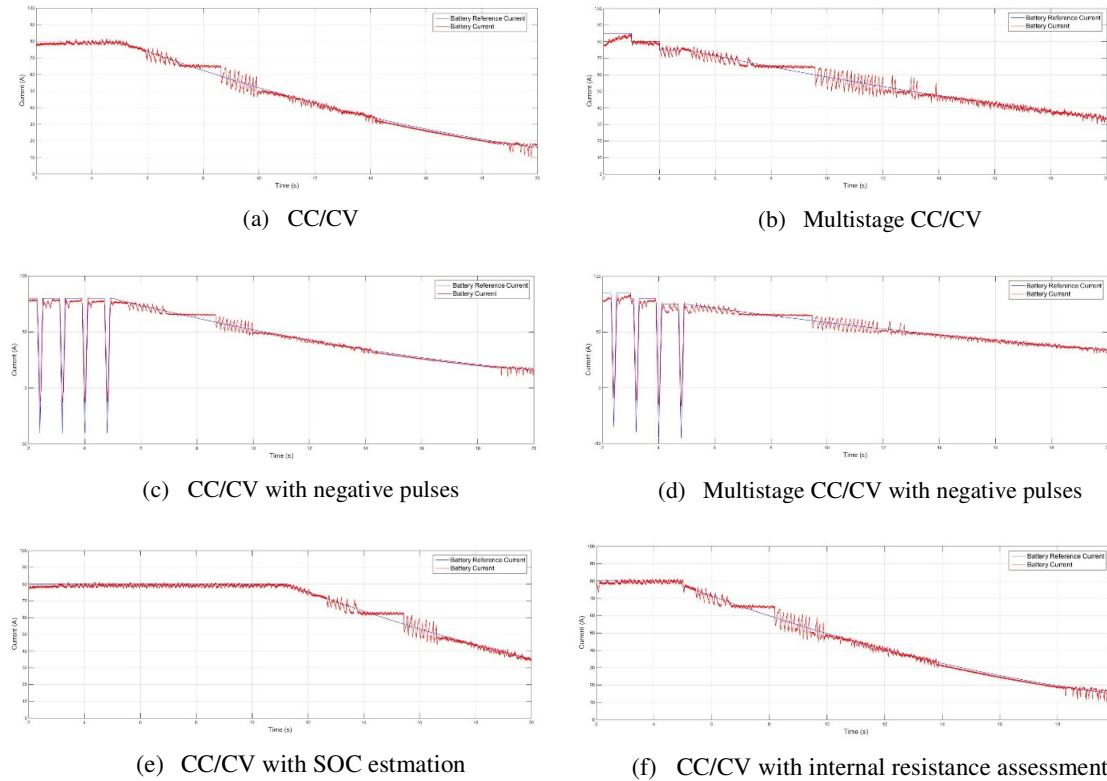


Figure 7: Battery current during different charging techniques

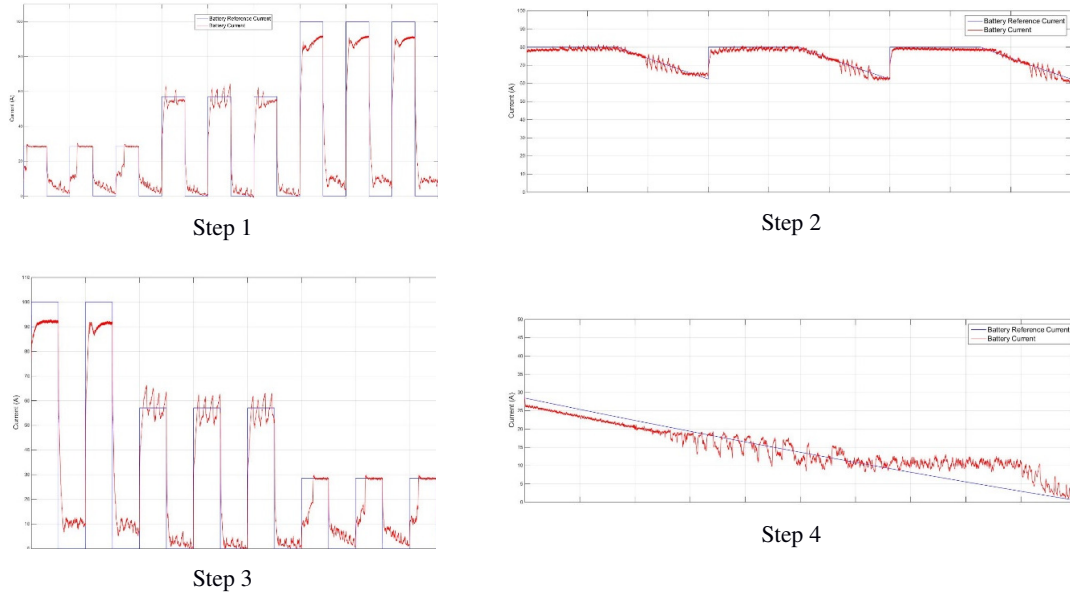


Figure 8: Positive pulsed current

Fig. 9 represents the battery voltage, current and SOC respectively during the CC/CV charging process, which clearly shows how the SOC increasing rate slowly reduces when the battery switches from the CC to the CV stage.

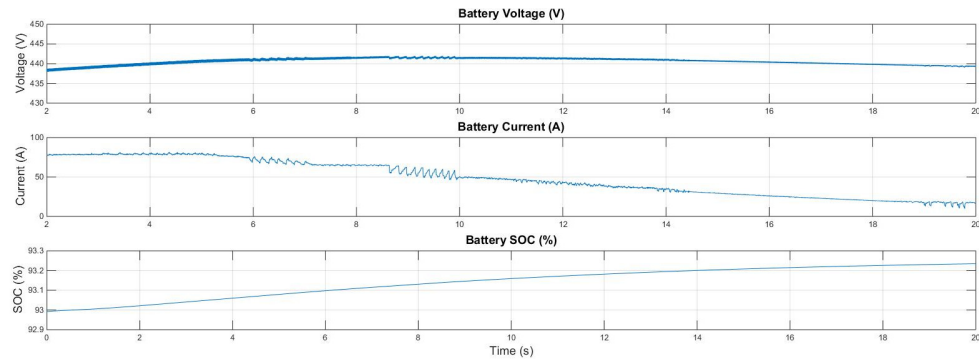


Figure 9: Battery voltage, current and SOC during the transition from CC to CV

6 Comparison of the charging techniques

The comparison between the different charging methods shows the effect on the battery and the converters in terms of switches and efficiency.

Table III resumes the maximum current and voltage on the AC/DC and DC/DC converter switches.

Table III: Voltage and current stress on converter switches

	AC/DC converter		DC/DC converter	
	Voltage (V)	Current (A)	Voltage (V)	Current (A)
CC-CV	450	210 (bidirectional)	450	200

Multistage CC-CV	450	210 (bidirectional)	450	200
CC-CV with negative pulses	450	210 (bidirectional)	450	200 (bidirectional)
Multistage CC-CV with negative pulses	450	210 (bidirectional)	450	200 (bidirectional)
CC-CV with SOC estimation	450	210	400	200
CC/CV with Internal Resistance assessment	450	210	400	200
Positive pulses	450	210	400	200

This table shows that the methods that include negative pulses require bidirectional switches in the DC/DC converter, which is an additional feature that exists only with the bidirectional chargers if they are used in a V2G (Vehicle to Grid) aspect.

Table IV shows the efficiency of both the AC/DC and the DC/DC converter while using every charging method mentioned in this paper.

Table IV: Converters' efficiency

	AC/DC converter efficiency (%)	DC/DC converter efficiency (%)
CC-CV	86	87
Multistage CC-CV	86.5	87.6
CC-CV with negative pulses	83	82.5
Multistage CC-CV with negative pulses	83.4	83.3
CC-CV with SOC estimation	85.3	86
CC/CV with Internal Resistance assessment	86	86.9
Positive pulses	77	83

Table V shows the effects of every charging technique on the EV battery.

Table V: Impact on the battery

	Final SOC (after 20s of charging) (%)	Current ripple (%)
CC-CV	93.24	5
Multistage CC-CV	93.27	4.1
CC-CV with negative pulses	93.22	2.5

Multistage CC-CV with negative pulses	93.27	1.25
CC-CV with SOC estimation	93.33	3.75
CC/CV with Internal Resistance assessment	93.24	4.37
Positive pulses	93.5	3.25

Fig. 10 summarizes the characteristics of every method in a spider graph, according to the different criteria mentioned in the paper. The method that is strong in a certain criteria receives the furthest point from the centre of the graph.

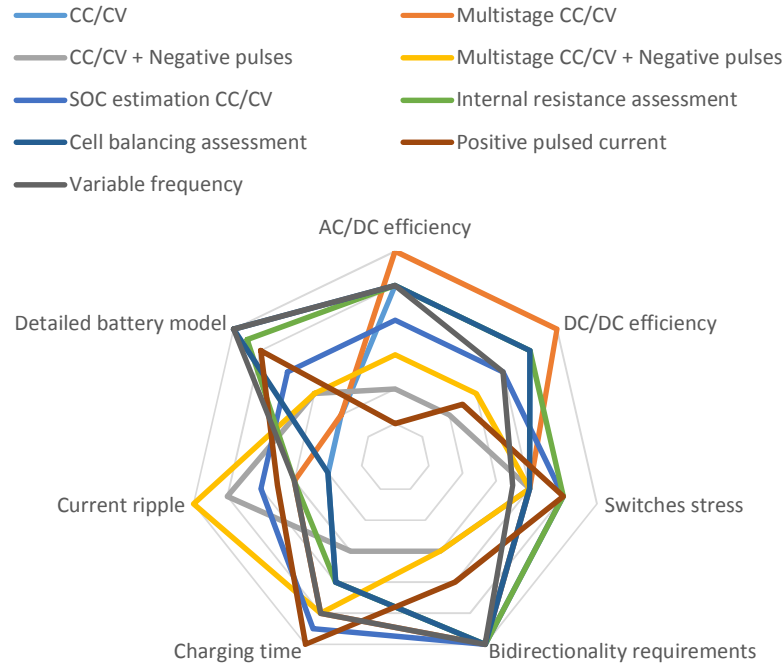


Figure 10: Spider graph comparing the charging methods

7 Conclusion and discussion

The simulations shown in this paper compare between different charging techniques, ranging from the conventional CC/CV and some of its variants, to methods specially proposed and dedicated to fast charging.

Fig. 10 details the different criteria used to compare these techniques. These criteria cover the converters composing the charger (their efficiency, requirements and voltage and current ratings), and the battery performance (charging time, detailed modelling and current ripple).

The CC/CV charge is clearly no longer adapted for fast charging of EV batteries. Its multistage variant however offers a good alternative, while maintaining the simple control and implementation. Adding negative pulses to these two methods has a purpose of allowing the battery to increase its charging acceptance but has a negative effect on the converters by forcing it to be bidirectional and on the switches by increasing their ratings. The charging time is reduced by adding these pulses because of the brief discharging periods.

Estimating the battery SOC and using it as a reference instead of the battery voltage has proven to be effective by further decreasing the charging time while maintaining an acceptable design and control. All the methods mentioned above pay little attention to the internal phenomena that happen especially with the fast charge, such as the voltage drop due to the internal resistance and cell unbalances. The two corresponding methods are very similar to the CC/CV charging, but with a constant check on specified characteristics. Alternative

methods that use multistage CC/CV while making sure that the internal resistance and the cell balancing are a good candidate for future fast charging techniques.

More sophisticated measures that are specifically designed for batteries, such as the positive pulsed and the variable frequency methods require detailed studies on the battery used and offer good results concerning the charging time and the battery performance, but can come at the expense of the efficiency of the electronic components.

Future work should focus on developing methods that take into account the developed battery model and the phenomena that happen during the fast charging, while making sure that the design of the charger remain within an acceptable margin of cost and simplicity of the control.

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