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A Critical Review on The Effects of Pulse Charging of Li-ion Batteries

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Abstract—In this paper a review on the effects of pulse charging of lithium based battery technology is done. Results published in existing literature are not in complete agreement regarding the effects of pulse charging. Several studies claim to have beneficial effects on charging efficiency, charging time, and capacity fade. While others have found disadvantageous effects on the same parameters. The goal of this paper is to summarize and review these results, based on fundamental theory. Additionally, it will be shown that the electrical equivalent circuit analysis of batteries, often used to explain the beneficial results of pulse charging is an incomplete analogy to fully explain the results of pulse charging.

Index Terms—Lithium ion, Battery Charging, Pulse charging, Sinusoidal Ripple Charging,

I. INTRODUCTION

Battery technology is already widely spread into today's society and has become a vital part of many devices on which we rely on in our daily lives such as laptops, phones, medical devices and uninterruptible-power-supply applications. With the increasing spread of renewable energy and electrical transportation, the penetration of batteries as stationary or vehicular technology is also increasing. Most modern applications use lithium-based technology due to their high energy/power density, high efficiency and good lifetime [?]. A conventional charging profile consists out of two phases [1]. The first phase is the Constant-Current (CC) phase, where the battery (cell) is still below its maximum allowable cell voltage, and a constant current can be applied to the battery (cell) until the battery voltage has reached its maximum allowable cell voltage. Then the second phase, the Constant Voltage (CV) phase, is reached. The charging current is then reduced such that the cell voltage is maintained at its maximum allowable cell voltage.

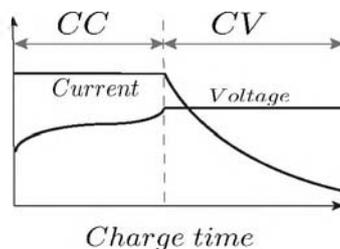


Fig. 1. Standard CC-CV charging profile

Combined, this is called CC-CV charging, and a depiction is shown in Fig. 1. One of the disadvantages of the CC-CV charging profile is the long charging time due to the long CV region [2], especially at high C-rates when the CV region is reached at lower SoC. Additionally, the constant current rate inside the battery causes an internal potential build up around the electrodes due to concentration polarization. This is claimed to cause an increase in battery ageing and poor utilization of active materials [2]. In order to overcome these effects, researchers are investigating new charging methods to improve battery performance and increase their lifetime. Studies have presented fuzzy logic and other complex charging algorithms to do this [3]–[5]. However, these methods tend to be very complex and not applicable to all applications [6]. Another solution proposed in literature is so-called pulse charging (PC), here batteries are charged with current pulses (square, triangular or sinusoidal) and researchers have presented results with increased charging efficiency [?], [1], [7]–[10], reduced charging time [1], [8], [10], [11], and decreased battery aging [8], [12]–[14], among others. However, other studies have also found negligible or even negative effects [13], [15]–[17]. Therefore, the goal and contribution of this paper are to investigate and review what the effects of PC are on lithium-based batteries. Additionally, investigate why certain studies have found beneficial effects while others claim negligible or disadvantageous effects. In this paper, the term PC is used as a reference to both square wave PC and sinusoidal ripple charging.

In order to do this, Section II provides a short review of basic battery theory. Afterwards, a review of papers discussing pulsed battery charging is done in section III. section IV gives a summary of the argumentation of the results and applies the fundamental knowledge of section II. Finally, the conclusion and future work are presented in section IV and V, respectively.

II. FUNDAMENTAL BATTERY THEORY

A schematic representation of a lithium-based battery is shown in Fig. 2. They consist of an anode and cathode placed in an electrolyte and separated by a separator. For Li-ion batteries, the anode usually is made out of graphite, whereas the cathode is made out of several composite materials depending on the application of the battery. Commonly used

materials are Cobalt, Manganese, Nickel, Iron, Phosphate and Aluminium. Battery characteristics such as power/energy density, thermal stability and cost can be varied by varying the composition of these materials. When a positive voltage is applied above the battery voltage, Li^+ ions de-intercalate from the cathode, move through the electrolyte and separator, after which they intercalate in the anode. According to the conventional current model, the current flows from the anode to the cathode.

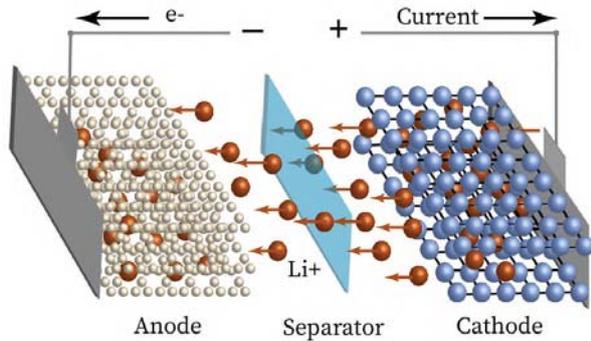


Fig. 2. Schematic representation of Li-based battery

The efficiency with which the ions and electrons move through the electrolyte, separator and intercalate in the anode/cathode determines the battery (dis)charging efficiency. The charge (also called coulombic or faradaic) efficiency is the ratio of the amount of charge extracted out of the battery to the amount of charge put into the battery during a full cycle [6], [18]. While the figure above is useful for visualising the operation of a battery, in order to gain a better understanding on the effects of PC a small review on relevant electrochemical theory is presented in the next subsection.

A. Electrochemical theory

The two main phenomena in batteries are 1. charge transfer; the transfer of electrons between molecules and 2. mass transfer; the transfer of ions. This is governed by two processes: migration and diffusion. Diffusion is caused by a gradient in concentration, while ion migration is caused by the applied external electric field. Both forces have different directions. Usually, diffusion is the dominant process for mass transport [19]. The dynamics of the diffusion processes can be described using Fick's law:

$$N_i = -D_i \frac{dc_i}{dz} \quad (1)$$

where,

- N_i Flux of i
- D_i Diffusion coefficient of i
- c_i Concentration of i
- dz Direction of mass transfer

Diffusion occurs at several locations in the battery; within the electrode, in the electrolyte and the solid-electrolyte-interphase (SEI) [19]. However the diffusion at the electrode is usually

the limiting process [2]. Due to the different time constants of the diffusion processes an internal potential build up can increase the over-potential [19], this then effects the charge transfer resistance, which can be derived from the Butler-Volmer equation. The Butler-Volmer equation is one of the most fundamental equations in electrochemical kinetics, it describes the total current density J based on the electrode over-potential $(E-E_0)$, considering both cathodic and anodic reaction occur at the same electrode [18], [20], the equation is shown in eq.(2).

$$J = J_0 \left(e^{-\frac{\alpha n F}{RT} (E-E_0)} - e^{\frac{(1-\alpha) n F}{RT} (E-E_0)} \right), \quad (2)$$

where,

- J Electrode current density
- J_0 Exchange current density
- R Universal gas constant
- T Temperature
- α Charge transfer coefficient
- n Number of electrons in the electrode reaction
- F Faraday constant

If the applied battery current is higher than the exchange current, a negative over-potential occurs inside the battery. This over-potential can cause lithium plating, which is a common aging factor in graphite based lithium batteries [1]. Another significant phenomenon occurring in batteries is the double-layer effect [1], [19], [20]. The double-layer effect describes the accumulation of charge around the electrode. It is a combination of the electrochemical potential (a definition used to describe the reluctance/willingness of particles to be added to a specific location) and the charge-transfer reaction described by the Butler-Volmer equation [19]. Since this accumulation of charge is voltage-dependent, it is also often called the double-layer capacitance and can be modelled using a combination of R and C components.

B. Equivalent Circuit Modelling

Electrochemical differential equations describing the dynamic behaviour of batteries tend to get very complex and difficult to work with from an engineering perspective. Therefore engineers usually use electrical equivalent circuit models [8], [10], [16]. An example of a Li-ion battery equivalent circuit is shown in Fig. 3. To start, R_Ω is used to approximate all ohmic losses inside the battery, including the resistance of the current collectors, battery terminals, internal connections and the electrolyte [2]. Next, a combination of RC networks is used, where two resistors model the charge transfer losses inside the battery R_{ct1} and R_{ct2} . The two capacitors $C_{D,L,1/2}$ represent the double-layer capacitances near the electrodes. Finally, the diffusion processes in the electrolyte and the electrode are described using the two Warburg elements $Z_{D,T}, Z_{D,R}$ [20]. A Warburg impedance is an equivalent circuit component which models diffusion processes and has a constant phase of 45° . It describes the low-frequency behaviour of the battery below 1 Hz [21]. Instead of using this Warburg impedance, additional

RC circuits can be used to model the diffusion processes. Here the accuracy of the model can be increased by increasing the number of RC circuits. In reality, the impedance is varying with SoC, C-rate, temperature and age [19]. Therefore in order to get a truly accurate equivalent circuit model, variable components combined with look-up tables have to be used such that the model is accurate over the entire operating range. Additionally, ageing models are needed to describe the ageing behaviour. The component values for the equivalent circuit model can be determined by curve fitting experimental data such as the impedance spectrum, open-circuit voltage and the intercalation capacitance [20]. In order to determine the impedance spectrum of a battery, Electrochemical Impedance Spectroscopy (EIS) is used. This will be described in the next subsection.

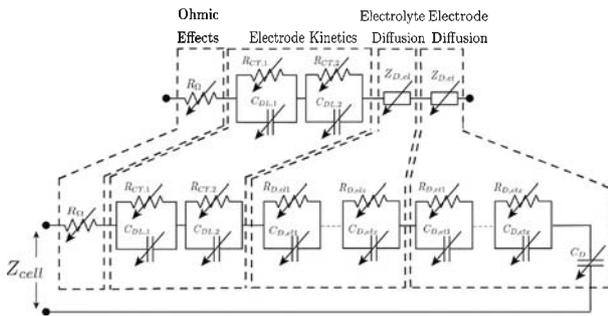


Fig. 3. Equivalent AC impedance model of a battery

C. Electrochemical Impedance Spectroscopy

When performing Electrochemical Impedance Spectroscopy, a battery is perturbed with a small AC voltage which is then used to find the impedance spectrum. When performing an EIS, it is important that the perturbation signal does not have a DC offset, since this would charge the battery and therefore corrupt the results due to the SoC dependency of the impedance. Fig. 4 shows the result of an EIS, here the SoC dependency of the battery impedance can be clearly seen. The frequency where the impedance Z is minimal is equal to the point where the imaginary part $\Im\{Z\}$ equals zero. Additionally, the point where the real part of the impedance $\Re\{Z\}$ is minimal is often close to or equal to this frequency. From now on this frequency will be referred to as f_{Zmin} , this frequency is often used when performing PC in order to determine the optimal pulse frequency.

III. REVIEW OF PULSED BATTERY CHARGING

In this section, a comparison of the results of the reviewed papers is presented. In order to have a fair comparison, a distinction is made between percentage and percentage points: in the following analysis the term percentage points will be used as a unit difference between two percentages. For example, when an efficiency is increased from 90% to 95% an increase of 5% percentage points is reported. All the reviewed papers can be found in Table I. Here, the colour of the 'Results' cell indicates whether positive or negative

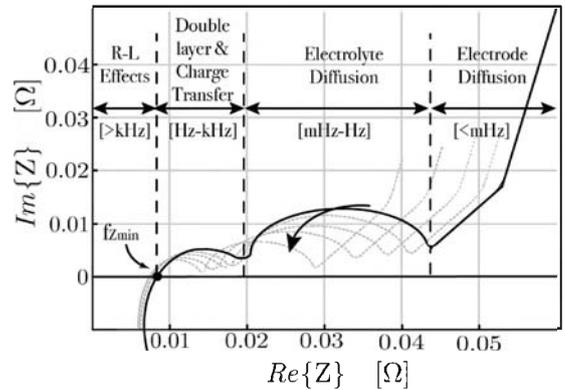


Fig. 4. Typical battery impedance spectrum, with the different processes indicated with their according frequency ranges

results were obtained from PC. Additionally, the single to last column indicates whether the authors have paid attention to the minimum impedance frequency or not. Furthermore, some studies are reported twice in the table in order to make a distinction between advantageous and disadvantageous results reported in the same study.

A. Charging frequency & f_{Zmin}

In [13] cells were charged with frequencies of 0Hz, 10Hz, 55Hz, 254Hz and 14.8kHz. Here an increase in 3 percentage points of capacity fade was observed at the cells charged with the highest frequency. The other frequencies showed similar degradation with respect to DC charging, after 1200 cycles. In [15] the effect of a 120 Hz ripple was analysed, here an increase of 1.3 percentage point capacity fade was seen. In these papers the increase in capacity fade can probably be explained by the increase in RMS current caused by the ripple/pulse, additionally at frequencies above f_{Zmin} , $\Re\{Z\}$ starts increasing again therefore very high frequencies tend to increase the losses (assuming that the current is controlled by the charger). The results obtained from [22]–[24] show no correlation of the AC ripple/harmonics with respect to the (dis)charging performance. Whereas, most of the other reviewed papers report advantageous effects with respect to efficiency, charging time or degradation. It should be noted that most of the studies reporting disadvantageous effects have taken no regard with respect to the minimum impedance frequency f_{Zmin} . Additionally, based on the last two columns shown in Table III-A, it can already be concluded that irrespective of the battery chemistry, battery performance in general improves when the battery is charged at or around the minimum impedance frequency f_{Zmin} . However, in [19] the authors have found that PC, with a pulse frequency equal to f_{Zmin} can lead to a small but negative decrease in efficiency of 0.1 ± 0.06 , 0.12 ± 0.06 and 0.09 ± 0.06 percentage points for sinusoidal, square or triangular PC.

TABLE I
REVIEW OF THE REPORTED EFFECT OF PC ON BATTERY PERFORMANCE. THE COLOURS INDICATE WHETHER THE FOUND RESULTS WERE BENEFICIAL (GREEN) OR NOT (RED).

Study	Year	Chemistry	Conditions	f_{Zmin}	Results
[16]*	2011	LiCO ₂	1A, 1-100Hz square pulse	x	Cells cycled below 100 Hz showed an increase of 1% percentage point of faded capacity compared to DC charged cells.
[15]	2013	LiFePO ₄	1C 100/120Hz rectified pulse	x	efficiency: 89-88% DC, 87.5 - 86.5% AC. The capacity drop after 2000 cycles was 15.1% for DC charging and 16.3% for PC. (1.5% difference is within measurement error range). Additional advantage; system does not need a PFC.
[25]	2012	LiFePO ₄	AC 120 Hz superimposed ripple	x	AC and the resulting temperature increase might lead to accelerated aging.
[13]	2017	LiNiCoAlO ₂	20% superimposed ripple of 1.2C i_{p-p} at 10Hz, 55Hz, 254Hz and 14.8kHz	x	After 1200 cycles, an average capacity fade around 18% is seen at the higher frequencies of 254Hz and 14.8kHz, compared to 15% for DC charging. At 55 Hz similar aging was observed as for DC charging. The power fade increases when the frequency increases, up to 15% at 14.8kHz compared to 10.5% at DC.
[18]	2018	LiNiMnCoO ₂	superimposed triangular, sinusoidal and square pulse of 60%Idc at 1C, 228Hz, 158Hz	✓	The AC charged cells showed a small decrease in efficiency between [0.09-0.12]±0.06 percentage point. Charging times where increased, however CV region was not taken into account.
[17]	2016	not specified	Pulsed ripple, 100%Idc, 0.5C at 2kHz	✓	The charging time decreased with 0.62% for, however efficiency decreased with 0.4%.
[23]	2017	LiCO ₂	superimposed ripple of 75% at 1C, 20Hz	x	The authors found that the RMS value of the current has a statistically significant effect on aging effects. Neither frequency or wave shape of the superimposed AC signal had any significant effects on aging.
[24]	2019	LiNiMnCoO ₂	superimposed ripple of 75% Ip at 1C, 1Hz, 100Hz, and 1kHz	x	The AC harmonics do not affect the capacity nor power fading of the cells.
[22]	2013	LiPo (NMC or LTO)	1) 2% ripple triangular 2) Charge depleting test 3) Charge sustaining test 4) Hybrid Pulse Power Characterization Test	x	Results show no direct correlation of increased aging due to the existence of a current ripple.
[26]	2015	LiMn ₂ O ₄	120Hz superimposed ripple	x	After 800 testing cycles the capacity of the sine charged battery was reduced by 3.9% and by 4.2% for the DC charged battery.
[27]	2011	LiCO ₂	square pulse at 0.2, 0.5, and 1 C, 200Hz, 25% duty cycle	x	PC helps in preventing solid-electrolyte-interface growth, this helps in increasing cycle life and maintaining long-term stability.
[16]*	2011	LiCO ₂	1A, 1Hz - 100kHz square pulse	✓	The capacity fade of cells (dis)charged at frequencies above 100Hz showed similar degradation as trickle-charged cells. From this it can be concluded that calendar aging effects are dominant when charged at these frequencies. After 147 days the cells cycled at f_{Zmin} had the least capacity fade of 6.5%, whereas the DC charged cells showed 14% degradation.

Study	Year	Chemistry	Conditions	f_{Zmin}	Results
[2]	2001	LiCO ₂	0.5C, 1C square pulse, including discharge pulse	✓	PC increases power transfer rate and maintains a better structure stability of the cathode active material (based on X-ray diffraction and scanning electron microscopy). The pulse charged cells were cycled with 1600 cycles before reaching 77.8% relative capacity, where the DC charged cells only had 700 cycles.
[11]	2019	LiFePO ₄	superimposed ripple of 50% $I_{dc} = 5A$, 0.5C at 50-400Hz	✓	Using sinusoidal ripple current charging 80% SoC was reached 10% faster compared to CC-CV charging. Furthermore, temperature was approximately 0.5° lower during the SRC charging process.
[14]	2018	LiNiMnCoO ₂	superimposed ripple of 90% at 0.25C, 1Hz - 30kHz	✓	The least aging was observed for cells cycled at the f_{Zmin} . After 3000Ah throughput the relative capacity was 0.963 and 0.958, for cells cycled at f_{Zmin} and DC, respectively. At very high frequencies, similar capacity fade was observed compared to DC. At lower frequencies, >30Hz the relative capacity was to decreased to 0.948 .
[21]	2013	LiNiMnCoO ₂	superimposed sinusoidal ripple of 100%Idc at 1C, 1Hz, 100hz, 998(fzmin) and 10kHz	✓	For pulsed charging the charging time, charging efficiency, the maximum temperature, and lifetime of the Li-ion battery are improved by about 17%, 2%, 45.8% and 16.1%, respectively compared with the conventional CC-CV charging strategy. For SRC the charging time, efficiency, and maximum temperature of the Li-ion battery are improved by about 0.24%, 0.27%, and 16.47%, respectively. Compared with the pulsed current charging strategy.
[1]	2015	LiNiCoAlO ₂	Sinusoidal ripple of 50%Idc at 0.375C, 1Hz, 10Hz, 50Hz, 100Hz, 300Hz and f_{Zmin} (400-600Hz)	✓	An increased ripple at the optimal frequency leads to higher charging temperature but lower discharging temperature, while the efficiency remains the same. At the optimal charging frequency with 50% sinusoidal ripple 1C, the charging time and efficiency are improved by 5.1% and 5.6%, respectively. Compared to CC-CV charging.
[6]	2018	LiPo	Pulsed charging with 50% Duty cycle at 1C, 12.6kHz	✓	Using the proposed charging scheme the energy and charge efficiencies improved by 11.3% and 1.5%, respectively, and decreased charge time by 47.6%. Compared to CC-CV charging at 0.5C.
[17]	2016	not specified	Sinusoidal ripple, 100%Idc, 0.5C at 2kHz	✓	The charging time decreased with 1.5%. The efficiency improved by 0.2 percentage point.
[7]	2017	not specified	Sinusoidal ripple of 100% Idc at 0.2C at 434Hz	✓	The ohmic losses were found to be reduced by 52% compared to CC-CV charging, using the proposed charging scheme.
[8]	2013	not specified	superimposed sinusoidal ripple of 50%Idc at 1 Hz, 10 Hz, 100 Hz, 10 kHz, and fzmin.	✓	discharging capacity, discharging efficiency, and rising temperature are improved by about 1.3%, 1.32%, and 41.9%, respectively, by using the proposed SC strategy at fzmin.

B. Efficiency

Seven of the reviewed papers report an increase in efficiency. Here the increase in efficiency ranged from 0.2 to 5.6 percentage point. Whereas, [15], [18] have shown a slight decrease in efficiency of 1.5% and 0.12 ± 0.06 percentage point. It should also be noted that the authors of [18] have done a thorough analysis of the maximum error based upon the equipment used. Therefore the results are not believed to be caused by possible measurement errors. The effects on efficiency are summarized Table II.

TABLE II
RESULTS ON CHARGING EFFICIENCY

Paper	η_{CC-CV}	η_{pulse}	f_{Zmin}	Cathode chem.
[1]	93.3%	98.9%	410-500 Hz	$LiFeMgPO_4$
[15]	89%	87.5%	x	$LiFePO_4$
[18]	96.32%	96.23%	158-228 Hz	$LiNiMnCoO_2$
[8]	97.0%	99.0%	998 Hz (SIN)	$LiNiMnCoO_2$
[8]	97.0%	98.6%	998 Hz (SQR)	$LiNiMnCoO_2$
[6]	89.24%	92.36%	146 kHz	V_2O_5
[6]	94.59%	97.86%	464 kHz	Li_xMnO_y
[10]	98.4%	99.9%	12.6kHz	$LiPo$
[21]	97.93%	98.88%	1.65kHz	/

C. Charging Time

Another motivation for PC is the reduction in charging time; these results are summarized in Table III. Also here most reviewed papers mention a decrease in charging time, ranging from 10% [11] to 47.63% [10] decrease. In [18] an increase in charging time of 0.76%, 1.03% and 1.19% for sinusoidal, triangular and square wave PC is reported. However, it should be noted that here the CV region phase is not taken into account, which results in an unfair comparison (this is also shown in [17], where the PC options only show a decrease in charging time when the CV region is taken into account). Additionally, due to minor calculation errors in the current control of the used instrumentation, the average current was higher for the DC charging case. Furthermore, in [17] a small decrease in efficiency and increase of charging time has been found when using square wave PC, while, sinusoidal PC is reported to have beneficial results for both efficiency and charging time. A possible explanation for this can be the increased impedance for the higher frequency harmonics, which are part of the square wave.

TABLE III
RESULTS ON CHARGING TIME

Paper	t_{CC-CV}	t_{pulse}	f_{Zmin}	Cathode Chem.
[1]	173.8 min	164.9 min	410-500Hz	$LiFeMgPO_4$
[11]	122.5 min	110.25 min	50-400Hz	$LiFePO_4$
[8]	72.8 min	60.5 min	998 Hz (SQR)	$LiNiMnCoO_2$
[8]	72.8 min	60.4 min	998 Hz (SIN)	$LiNiMnCoO_2$
[6]	83 min	47 min	146 kHz	V_xO_x
[6]	90 min	76 min	464 kHz	V_xO_x
[10]	135 min	70.7 min	12.6 kHz	$LiPo$

D. Degradation

Finally, the results regarding degradation are summarized in Table IV. For details about the number of cycles, please refer to the actual papers. Studies [15] [16] [13] have found that superimposed AC ripples or pulses can have negative effects on the degradation of Li-ion cells, ranging from 1 to 3 percentage point increase in capacity fading. As mentioned earlier, the most probable reason for this increased ageing is the increased RMS current as well as a deviation from the minimum impedance frequency. In [16], both an increase and decrease in capacity fading is reported. Here pulse frequencies below 100Hz showed an increase of approximately one percentage point compared to DC charging, whereas the least capacity fading was observed for the pulse frequency close to f_{Zmin} with a reduction of 7.5 percentage point. Similarly, [13] showed similar ageing (compared to CC-CV charging) when pulse charging with a frequency close to f_{Zmin} , and an increase in ageing up to 3% for higher pulse frequencies. In [2], the pulse charged cells are able to perform 1600 cycles before reaching 700mAh (78% of the nominal capacity), whereas the DC charged cells only 700 cycles. However, here it should be noted that the initial capacity of the pulse charged cells is around 1200mAh, whereas the DC charged cells around 1100mAh. Even though all cells are higher than the nominal capacity, the increased amount of cycles are partially due to the higher initial capacity. Nevertheless, it is shown that PC increases the power transfer, resulting in lower cell temperature and maintains better structural stability of the active material in the cathode and as a result of this reduces the ageing.

TABLE IV
RESULTS ON DEGRADATION

Paper	ΔCap_{CC-CV}	ΔCap_{pulse}	f_{Zmin}	Cathode chem.
[16]	14%	15%	$\leq 100Hz$	$LiCoO_2$
[16]	14%	6.5%	$\geq 100Hz$	$LiCoO_2$
[2]	700 cycles	1600 cycles	x	$LiCoO_2$
[15]	15.1%	16.3%	x	$LiFePO_4$
[13]	15%	15%	55 Hz	$LiNiCoAlO_2$
[13]	15%	18%	≥ 254 Hz	$LiNiCoAlO_2$
[14]	4.2%	3.7%	10 kHz	$LiNiMnCoO_2$
[8]	6.2%	3%	998 Hz	$LiNiMnCoO_2$

IV. APPLICATION OF THEORY

Here a summary of the argumentation behind the reviewed results is presented which applies the fundamental knowledge discussed in section II. In [8] [28] sinusoidal-ripple-current charging is claimed to increase the transfer efficiency by minimizing the impedance of the battery. However, it should be noted that AC impedance analysis based on electrical equivalent circuit modelling is an incomplete analysis since the DC component of the current is neglected. The Fourier transform of DC current with superimposed ripple current consists out of both the DC component, fundamental frequency and the summation of harmonics. This is shown in eq.(3)-(4) for a sinusoidal and square wave pulse, respectively.

$$i_{SRC}(t) = I_{DC} + I_{DC} \sin(\omega_0 t) \quad (3)$$

$$i_{\text{PRC}}(t) = I_{\text{DC}} + \frac{4}{\pi} I_{\text{DC}} \sum_{k=1, k:\text{odd}} \frac{1}{k} \sin(\omega_o kt) \quad (4)$$

Therefore, based on equivalent circuit analysis, any superimposed AC ripple should increase the losses due to the increased RMS current [1]. Furthermore, the DC resistance is a summation of R , $R_{ct1,2}$ and the resistances used to model the Warburg impedances, which is often much larger than the minimum AC impedance [17]. However, from the results shown above it is clear that the pulse frequency has a strong impact on the obtained results and that superimposed ripples/pulses can have strong advantageous results. Therefore it can be concluded that AC impedance analysis alone is a good method for determining the optimal charging frequency, but does not explain the obtained results. [1] argues that the obtained beneficial results are due to the charge/discharging of the double-layer capacitance. As discussed above, the charging/discharging of this layer affects the over-potential and hereby the total conductivity of the battery. Here pulsed charging could help in discharging this capacity reduce the over-potential and improve conductivity [29] [19]. In [2] [6] [8] it is claimed that PC reduces the internal potential build-up caused by a concentration polarization. As explained previously, this internal concentration polarization interferes with the movement of ions in the electrolyte, since it counteracts the diffusion process [2]. This is in line with the results obtained in [7], where experiments have found that the internal impedance of a Li-ion battery can be reduced by 52% from 0.25Ω to 0.12Ω , when PC at the optimal frequency f_{Zmin} is performed. Furthermore, PC is claimed to increase battery life since it decreases the amount of incomplete chemical reactions, and reduces the increase of battery impedance [6], by preventing parasitic reactions such as lithium plating [2]. Similarly, [14] claims that AC ripples interact with the different processes inside the battery each with different time constants. Depending on the frequency, different superimposed AC ripples or pulses can activate these different processes and therefore influence the ageing behaviour of the cells. This is consistent with the conclusion from the previous section that the pulse frequency is a crucial parameter which determines whether PC has advantages over regular CC-CV charging. In most studies, f_{Zmin} is tracked or analyzed using EIS and/or equivalent circuit analysis.

V. CONCLUSION

In this paper, a summary and review on the effects of pulsed charging of Li-ion batteries have been performed. This includes sinusoidal, square and triangular pulses. It has been shown that most of the reviewed papers report advantageous effects in terms of charging efficiency, charging time, and battery degradation. However, results are not uni-lateral. Furthermore, a strong correlation of the results with pulse frequency has been found. More specifically, when charging with a pulse frequency equal to the minimum impedance frequency, ten out of twelve reviewed studies claim positive results. No correlation with cathode chemistry has been found.

A consensus exists that these results can be explained by the prevention/reduction of an internal gradient build up in the electrolyte and the double-layer capacitance. Which increases conductivity and as a result of this improve efficiency, charging time/power transfer rate and ageing.

VI. FUTURE WORK

The current study could be elaborated by further investigation on the effect of pulse charging conditions such as duty cycle and harmonic content. Additionally, work is needed to investigate the potential benefit of pulse charging when taking into account the effect on the power electronics, control as well as the battery management system (cell balancing, SoC estimation). Finally, the effect of a PC on a battery pack as a whole can be investigated, especially the optimal frequency tracking of a battery pack level.

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