Mediterranean Journal of Basic and Applied Sciences (MJBAS)
Volume 8, Issue 1, Pages 22-36, January-March 2024

Pulse-Charging Techniques for Advanced Charging of Batteries

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DOI: https://doi.org/10.46382/MJBAS.2024.8104

Article Received: 15 November 2023 *Article Accepted: 21 January 2024* *Article Published: 30 January 2024*

ABSTRACT

Batteries are remarkable devices. Nowadays, they power devices everywhere, from small children toys to IoT devices, cellphones and automobiles, especially rechargeable ones. The need to have healthy batteries ready to be reused in a very short time is essential. Unfortunately, charging a battery is a trivial task that can lead to battery degradation and wear, even thermal escape and fire. The faster the charging process, the more the problems that arise in the charging battery. In this work, several charging algorithms and noteworthy, although mostly unknown, methods are presented and commented. For example, a common algorithm that produces good charging results is the Constant Current/Constant Voltage, abbreviated CC/CV, that is used in most battery chargers. Yet, the pulse charging algorithm, as presented, exhibits remarkable results compared to the common CC/CV algorithm. The pulse charging methods, as evaluated, keep the batteries healthy, achieving better charging results and lower charging time.

Keywords: Battery; Charging; Chargers; Pulsed-Chargers; Lithium-Ion; Lead-Acid; Fast Charging; Pulse-Charging.

1. Introduction

Since the early days of electrical engineering, scientists seek for ways to power electronic appliances using devices that produce electric current when connected to an electrical circuit. The term “battery” was first used by the American scientist and inventor Benjamin Franklin in 1749, when he was doing experiments with electricity using a set of linked capacitors. During the ages, the battery technology advanced. Batteries, as devices that store chemical energy being able to convert it to electrical, became valuable inventions. Many of our devices nowadays are powered up by batteries leading to the need of being smaller and more powerful. Today they are so ubiquitous that they are almost invisible to most people as a remarkable invention they truly are [1].

From simple toys, to more advanced electrical and electronic circuits, as cellphones, IoT nodes and automobiles, batteries are the main powering devices, especially lead-acid and Lithium ones. Those batteries feed the circuits with electric energy, but they are also recharged when they reach a low state of charge, using another power source. There are several factors that contribute to the degradation of batteries over time [2-8], primarily associated to the charging and discharging processes. Choosing the correct charging process is fundamental to avoid fast wear and keep the batteries healthy for a longer time.

Considering the importance of batteries and their wide usage in appliances and technological applications, but also the increasing demand for improved methods of constructing, using and charging them [1], the present study has been conducted with the following objectives:

- in order to delineate the state-of-the-art technology in the relevant field;
- focus on the rechargeable batteries’ technologies;
- determine the recharging methods for rechargeable batteries;

- assess the recharging techniques and algorithms for rechargeable batteries, and
- compare pulsed-current charging techniques with others and with each-other.

2. Rechargeable Batteries

In demanding applications, the need for light weight batteries, storing as much energy as possible, being able to power very demanding circuits in terms of electric current and be charged in zero time is the absolute value of a battery. These demanding parameters force scientists and engineers-researchers to find better chemistries, other more appropriate materials to manufacture batteries and provide safety and increased performance.

Lithium-ion batteries are widely used in various electronic devices due to their high energy density and relatively low weight. During charging and discharging, lithium ions move between the positive and negative electrodes, causing chemical reactions that store and release energy. More specific during discharging process, when the battery powers the target circuit, lithium atoms loose an electron and become positive charged ions, Li^+, then they move from the anode into the cathode, where they are incorporated into its structure. The electron moves from the anode to the cathode through the external circuit, providing electric power to the external circuitry. During the charging phase, an external voltage is applied to reverse the movement of lithium ions. At the cathode, lithium atoms loose an electron and become positive, Li^+. Then they move to the anode and incorporate again to its graphite structure [9].

The most common type of rechargeable battery used in automobiles is the lead-acid one. According to Kelly [10], approximately 50% of the automobile batteries are abandoned when becoming incapable of keeping their charge any longer. A lead-acid battery tends to get acid when repeatedly charged, while it is recommended not to be discharged more rapidly than a twenty-hour period. It has been demonstrated though that pulse-charging may fully revive such a battery.

2.1. Degradation during charging cycles

Things in batteries are not ideal. There are several factors that contribute to the degradation of batteries over time. Discharging and charging processes play key roles to wear of these devices. In this part, although the reference is on Lithium-ion battery types, the same apply more or less to other chemistries [11-12]:

1. *Cycling*: Every charge and discharge cycle causes a small amount of degradation on the battery materials. The contraction and expansion of electrode materials can lead to their mechanical stress, which may result in the breakdown of the electrode structure over time.

2. *Overcharging*: Overcharging a lithium-ion battery can cause the formation of Lithium metal on the battery's anode, leading to dendrite growth. Between cathode and anode there is a thin separator. Dendrites, as tiny thin metal filaments they are, when growing, they pierce this separator, causing a short circuit within the battery, leading to thermal runaway and/or fire. Also, overcharging can cause electrolyte decomposition resulting into formation of gasses, leading to increased internal pressure within the device. Among those gasses are CO, CO_2 and H_2, CH_4, C_2H_4 and C_2H_6 [8].

3. *High temperature*: Exposure of a battery in high temperature, at any time of its life, accelerates their degradation. Elevated temperatures can cause chemical reactions that degrade electrolyte and electrode materials reducing its life cycle and performance.

4. *Depth of Discharge* (DoD): Batteries have a specific low level where draining them deeper can contribute to faster degradation. Shallower discharge cycles tend to be less stressful leading to longer life cycle.

5. *State of Charge* (SoC): Operating the battery at the most higher or most lower level of charge for a long time can contribute to its degradation. These conditions happen when the battery is always "in charging" state, causing the charger to fill it up again and again when even a small amount of its energy is given to the target load, like having a laptop always connected to its charger, or giving a small charge when the battery is at its lower level and then use it again to power up its load, like charging a little bit a cellphone, only to be able to keep it running for a small time.

6. *Calendar aging*: Even when not in use, batteries undergo aging due to chemical reactions over time. Temperature, electrolyte composition and other materials used in the battery are factors that can influence calendar aging.

7. *Impurities and contaminants*: The presence of impurities in the materials or manufacturing defects or contamination during the production process can contribute to the degradation of the battery.

Many of these factors can be addressed by using improved battery management systems, incorporating careful charging methods. Then, their overall performance can be increased and their overall lifespan can be expanded. As the charging algorithm and methods play a crucial role in the life cycle, performance, and safety of batteries, researchers actively explore improved techniques to expedite the charging process, while simultaneously meeting all requisite criteria.

2.2. Existing battery charging methods

The contemporary imperative for rapid and efficient battery charging has compelled the scientific community to explore enhanced charging algorithms. This paper outlines some of the most prevalent methodologies in this pursuit [13-22].

2.2.1. Trickle charging algorithm

Trickle charging is a charging algorithm used in certain battery management systems to maintain a fully charged state in a battery over an extended period. This method involves supplying a continuous, low-level current to the battery to compensate for self-discharge and other factors that may lead to a gradual loss of charge. Trickle charging is typically applied after a battery has been fully charged using a regular charging algorithm.

Trickle charging involves applying a very low current to the battery, usually well below its normal charging rate. This low current compensates for the self-discharge rate of the battery, preventing it from losing its charge over time. It is intended for long-term maintenance rather than rapid charging and is applied continuously or intermittently over an extended period, such as when a device is in standby mode or a vehicle is not in use. This type of charging is not suitable for all types of rechargeable batteries. Some modern lithium-ion batteries may have built-in protection mechanisms that make trickle charging unnecessary or even detrimental.

2.2.2. Constant voltage charging algorithms

Constant voltage charging is a charging algorithm commonly used for charging lead-acid and lithium-ion batteries. The primary characteristic of this charging method is that it maintains a constant voltage across the battery terminals. Most of the times this charging algorithm is used together with the constant current algorithm. In that case constant voltage is used at the final charging stage.

2.2.3. Constant current charging algorithm

The constant current charging algorithm is a common method used to charge rechargeable batteries. In this charging scheme, a constant current is applied to the battery until it reaches a predetermined voltage level. This algorithm is often employed in the initial stages of charging and is particularly suitable for lithium-ion and lithium-polymer batteries, which are prevalent in portable electronic devices, electric vehicles, and many other applications. Advantages of the constant current charging algorithm include fast charging as the initial constant current stage allows for a relatively quick charging process, especially in the early stages when the battery can accept higher currents. However, it’s essential to carefully manage the charging parameters to avoid issues such as overcharging, which can lead to safety concerns, reduced battery life, and other performance issues.

2.2.4. Pulse-charging algorithm

Pulse-charging is a battery charging algorithm that involves the intermittent delivery of short pulses of charging current to the battery. This method is designed to provide a series of controlled pulses rather than a continuous and constant flow of current. Pulse-charging is employed in various battery charging applications, and it is often used as part of more complex charging algorithms. This work is focused on pulse-charging, as it eliminates many drawbacks of other charging algorithms, and provides fast charging, safety, and longer life cycle for the batteries.

2.2.5. Combined CC/CV charging algorithm

A combination of the three charging algorithms, trickle charging, constant current and constant voltage, provides a multimode charging algorithm called Constant Current/Constant Voltage (CC/CV) charging algorithm. This multimode technique applies one of the three algorithms according to battery state of charge (Figure 1).

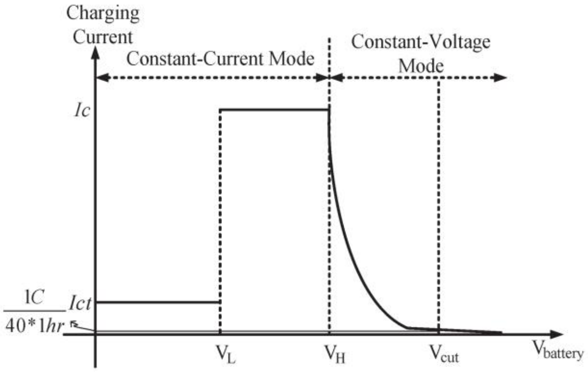

Figure 1. Three modes of battery charging, CC/CV algorithm [17]

When the battery voltage is under V_L, a low constant current I_{ct} is supplied to trickle charge the battery up to V_L level. This charging current is usually at a level less than or equal to 0.1C. As C, the energy capacity of the battery is denoted. So, considering a battery of 100mAh, the maximum trickle charging current is $I_{ct} = 10mA$. Above that level and up to V_H a constant current I_C is supplied that fast charges the battery up to V_H. This is the Constant Current charging phase, where the charging current can be from 0.5C and up to 3.2C, depending on the application and battery safety level [17, 23]. The battery voltage level increases rapidly up to near its final voltage value, due to the high charging current. Above the final level and up to the point where the battery has gained its maximum charge, the charger system changes to Constant Voltage mode. The applied voltage is at a sufficient level to slow charge the battery up to its maximum point, V_{cut}. The CC/CV algorithm is suitable for fast charging a battery. The drawbacks are that the faster the charging process, the more stressful the result for the battery. Also, the final stage, the Constant Voltage one, slows down the overall charging process.

3. Pulsed-Current Charging Techniques

Pulse-charging is the application of carefully controlled current pulses with the aim of charging a battery. It is an alternative technique for achieving fast charging and improved charging efficiency of a battery, without increased cost and complex charging algorithms. The art of pulse-charging can be traced back to the 1915 when David H. Wilson proposed a method to reduce the time required for energy storage in a battery [24]. The pulse-charging technique has gained the attention of OEM (Original Equipment Manufacturers) through products offered at today's market. They were mostly used for charging lead-acid batteries, especially due to its sulfur elimination properties. A pulse has the following parameters: Frequency/Period, Amplitude, and Duty cycle. By selecting the correct values for these parameters, a fast and safe charging, also having better performance in terms of energy loss, can be achieved.

3.1. Basic characteristics of Pulse-Charging for lithium-ion batteries

Using current pulses for charging a lithium-ion battery is beneficial. It provides faster charging than the other techniques described earlier. During charging, if the rate at which Li+ is electrochemically reduced at the graphite electrode, it is higher than the rate at which Li+ intercalates into the graphite (in the case of a high charging rate or approaching the end of charging), then accumulation will occur at the graphite-electrolyte interface, increasing the polarization of concentration and the potential for dendrite growth [25].

The constant voltage charging seriously extends the charging time. It is well-known that lithium ion diffusion in the electrode is the rate-determining step in the charging process. The slow lithium ion diffusion inevitably results in concentration polarization, especially at the high current charging, bringing the battery voltage rapidly to the upper voltage limit. Alternatively, the constant voltage charging drops the current to the preset limit before the active material in the electrode is completely utilized.

In order to overcome these problems, the pulse-charging can be used for lithium-ion batteries, where short relaxation periods are applied during the charging process. The short relaxation periods can effectively eliminate the concentration polarization and increase the power transfer rate, thus improving the active material utilization and accelerating the charging process [26].

Pulse-charging is also an effective method for increasing the life cycle of the battery. The imperfect chemical reactions that increase the internal battery impedance are eliminated, thus improving battery health. Applying charging current pulses with different parameters leads to different results in charging time, charging level, power transfer rate and life cycle. Different batteries react differently to the charging process under the same pulsed current parameters.

The dynamic response of batteries covers a wide frequency range, starting at frequencies of some μHz and ending at frequencies of some MHz. This wide range is caused by different physical effects, such as mass transport, the electrochemical double layer and simple electrical effects. Each effect has a typical frequency range; however, the typical frequencies depend to a great degree on the battery technology and the battery design [5]. In lower frequencies, the mass transport effects are more active, while on higher frequencies, the parallel combination of the double layer capacitance and load resistance starts affecting the charging process.

The duty cycle of the applied charging pulses also plays a vital role. Higher duty cycle provides faster charging but can lead to battery overcharging and overvoltage, due to increase of the polarization of concentration that reduces ion movement. Lithium batteries have poor tolerance to overcharging, which leads to temperature raise and thermal escape [3]. The peak current can also affect battery safety, since higher currents can lead to fast charging, but the risk of temperature raising and overcharging is also higher. Using higher charging current requires longer relaxation periods from pulse to pulse.

3.2. Various proposed pulse-charging algorithms

Several chargers utilizing pulse-charging algorithms have been proposed. Other studies have also been conducted regarding the application of pulse-charging with lead-acid and lithium-ion batteries. Various implementation methods of pulse regulation algorithms have been suggested, resulting in different charging times, charging efficiency, and lifecycle outcomes.

An approach is proposed of applying pulse-charging technique to multiple battery cells without supervisor. The target battery pack was formed by 80 cells connected in series and a battery management microcontroller was mounted on each battery cell. The system used an algorithm to search for the optimal frequency and duty cycle. This search mode finds the optimal frequency, while minimizing the cell impedance, using the highest charging current to reduce the energy consumption in the battery. The proposed charger uses a 50% duty cycle and adjusts the frequency range from 500 Hz to 5000 Hz by increasing the frequency by 500 Hz steps. After charging for five seconds by the selected frequency F_N, the charging current calculation is immediately performed by averaging the current in the last five seconds, followed by updating the corresponding current, I_N. If I_N is bigger than $I_{optimal}$, the $I_{optimal}$ and the corresponding $F_{optimal}$ will be updated with newer I_N and F_N, respectively. F_N will increase by 500 Hz steps until the frequency reaches 5000 Hz or the SoC reaches 0.8. The algorithms for calculating the optimum frequency and duty cycle is programmed in a microcontroller. The result was a faster charging by 18.6% compared to CC/CV algorithm [1].

Liang-Rui Chen [27] proposed a pulse charging algorithm using variable frequency. The system can detect and dynamically track the optimal charge frequency to improve the battery charge response. This algorithm was also programmed in a microcontroller and it achieved a faster charging time by 24% compared to CC/CV algorithm. A similar approach, but for optimum duty cycle detection is proposed by Purushothaman & Landau [28]. By charging the battery using different pulses with different duty cycles, the optimal duty cycle can be calculated. The algorithm achieved a charging time up to 14% less than common CC/CV. They also created a lithium battery model with which they analyzed different charging techniques using CC/CV and pulse-charging algorithms. Following their methods, they concluded that the lithium-ion battery can be fully charged in less than an hour using the proposed pulses, instead of the 3–4 h required for conventional charging.

From the previous works discussed, pulse-charging algorithms yield significant benefits when the parameters of the pulse current are appropriately selected. One of the drawbacks highlighted in these studies is the increased complexity associated with implementing the algorithms, resulting in the need for microcontrollers or microprocessors that consume additional power and space on the board. It is imperative to design a battery charging system that addresses these drawbacks, considering reduced charging time, enhanced battery charging, energy efficiency, safety, and compact design.

3.3. Pulse charging usage on IoT devices

In this section, we will delve into the design of a charger recently proposed, incorporating a pulse-charging algorithm that addresses the aforementioned drawbacks and also considers battery polarization throughout the entire charging cycle [29]. This charger targets applications of lithium-ion batteries ranging from the Internet of Things (IoT), such as smart thermostats, window shades, and door sensors, to portable devices like smart glasses, fitness belts, and digital styluses.

With IoT already reaching high levels of usage, there is a need for fast charging of devices that are constantly connected to the internet and consume continuous power. A battery or charging system failure in an IoT device can be catastrophic; therefore, there is a demand for compact charger circuits that are simple, cost-effective, easily integrable, and capable of rapidly, safely, and reliably charging batteries. These small devices sometimes use coin or button cell batteries for space-saving reasons. The pulse charger discussed in this section achieves a very compact size.

3.3.1. Theory of operation

The mentioned pulse charger can take its input from a continuous current voltage source and direct the charging current through different operational cycles to the battery, aiming to improve charging performance while concurrently reducing the charging time. Previous attempts incorporating pulse-charging algorithms did not include a pre-charging phase in the design, neglecting consideration for deeply discharged batteries. This pulse charger integrates:

- a pre-charging phase for deeply discharged cells and preparation purposes;
- a fast/slow charging phase to enhance battery charging performance and reduce charging time;
- a termination phase to avoid overcharging and overvoltage conditions.

All these phases can be user-programmable. Additionally, it incorporates safety mechanisms such as external battery temperature detection and overvoltage protection circuitry to safeguard both the user and the battery during charging [30].

It uses three modes: trickle charging, fast charging and slow charging. The proper charging mode is selected according to the current state of the target battery. If the battery is deeply discharged, then the trickle charging mode is enabled. Fast charging mode is selected when battery is again out of deep discharged state but under V_{nom}, which is the nominal voltage of the battery. When the battery voltage approaches the fully charged level (SoC 100%), the slow charging phase is entered.

As the battery approaches full charge, it is essential for the battery to efficiently absorb the load to prevent overcharging due to the increased concentration of lithium ions Li^+ at the electrodes during this phase. Polarization is initially high at low SoC, due to lithiation, and as SoC increases, polarization decreases. However, as SoC surpasses 80%, due to the difficulty of Li^+ intercalation, polarization increases again. Therefore, by altering the operational cycles during the charging process, the concentration polarization can be minimized to ensure proper intercalation.

The fast and slow charging phases aim to combine fast charging with increased battery charging performance and also take into account the polarization characteristics of the battery during charging. The charger should operate at a frequency where the resistance of the lithium-ion battery is minimal to reduce battery energy losses, improve battery charging, and enhance its energy efficiency. The choice of the charging pulse current waveform should also be considered. In the initial stages of charging, Li+ ions easily intercalate into the electrodes, but as the battery approaches full capacity, the polarization is much higher, as it takes more time for Li+ to intercalate into the anode. If higher duty cycles are used at this stage, Li+ is likely to accumulate on the electrode surface, which can lead to dendrite growth. Therefore, a method is proposed where faster charging, improved battery charging, and energy efficiency can be achieved without introducing overvoltage or overcharging conditions. Battery health and battery life are consequently enhanced. The charging phase is divided into two parts:

- one part provides fast charging using a higher duty cycle when the battery polarization is low,
- and the other part uses a lower duty cycle to allow better battery charging performance.

Due to the stringent charging requirements of a lithium-ion battery, a duty cycle of 70% or higher is suitable for the initial charging stage. Then, the duty cycle is reduced as the battery approaches full charge.

The operating cycle for the fast charging phase ranged from 10% to 90%, power consumption and charging time were measured. In this simulation, the battery was modeled as a 100F capacitor in series with a 100mΩ resistor. Energy consumption and charging time in relation to the fast charging duty cycle were recorded [30]. To achieve fast charging at relatively low power consumption, the fast charging duty cycle must be adjusted below 75%. Purushothaman & Landau [28] suggested that a 75% duty cycle was sufficient for fast charging, while also preventing lithium plating on the electrodes. To account for the high polarization of the battery towards the end of charging, the duty cycle was reduced to 25% to achieve improved charging performance.

3.3.2. Functions Results

The characterization of lithium-ion batteries before evaluating the properties of pulse chargers is essential. It is noteworthy that as the battery capacities increase, the frequency at which the minimum battery impedance appears decrease for the same cathode material. Therefore, the volumetric capacity of the battery, dependent on the crystalline structure of the materials used and the size of the battery, impacts both the impedance and the frequency at which the minimum battery impedance occurs. From the experiments it is evident that the battery with the smallest capacity exhibits higher ohmic resistances and charge transfer resistances. The capacity C_{dl} is also small due to the smaller electrode area and increases with the increase of battery capacity [30].

As for the charging time, the proposed pulse-charging algorithm reduced the charging time by 37% and 16% for the 100mAh and 45mAh lithium-ion batteries, respectively. Charging efficiency was improved by 3.2% in each case when the proposed pulse algorithm was used. The pulse algorithm was also tested at the frequencies of 50 kHz and 500 kHz, to determine the effect of charging frequencies on battery charging time and performance. Since the impedance is minimal at the optimal frequency f_{Zmin} and increases at all other frequencies, it can be inferred that there are much greater energy losses in the battery at frequencies other than that. At 50 kHz and 500 kHz, the reduction in battery charging efficiency was 13.95% and 11.98%, respectively, for the 45mAh lithium-ion battery. Therefore, the frequency at which pulse charging is performed is crucial and must be chosen carefully.

The alternating resistance of the battery at 50 kHz and 500 kHz was 3.8 ohms and 3.6 ohms, and 4.5 ohms and 4.4 ohms for the 45mAh and 100mAh lithium-ion batteries, respectively. Through the experiments, it is evident that using the proposed pulse-charging algorithm, operating at the frequency where the battery's alternating resistance is minimal, yielded the best battery charging performance, compared to the CC/CV charging algorithm as a reference [30].

3.4. Pulse-Charging Devices

Similar conceptually to the above but implemented differently are some mostly unknown devices of pulse-charging lead-acid and NiCad batteries. There are more than 15 such designs [10, 31, 32] of “passive” or “active” function. The difference between these two types is that the former has no moving parts but merely guiding circuits for making the charging pulses, like the previous category (see sections 3.1-3.3). Yet, the features of the pulses of this category differ significantly from those techniques of the previous one in four ways (see Figure 2, bottom):

- the shape of the pulse in not square but rather sharp triangular (spikes);
- their voltage is very high (at least 200V);
- their amperage is very low (no more than 400 mA);
- their frequency is also very high, ranging usually from 20 kHz to hundreds of MHz.

The “active” pulsing chargers are mainly based on the model proposed by Bedini [33, 34] (Figure 2).

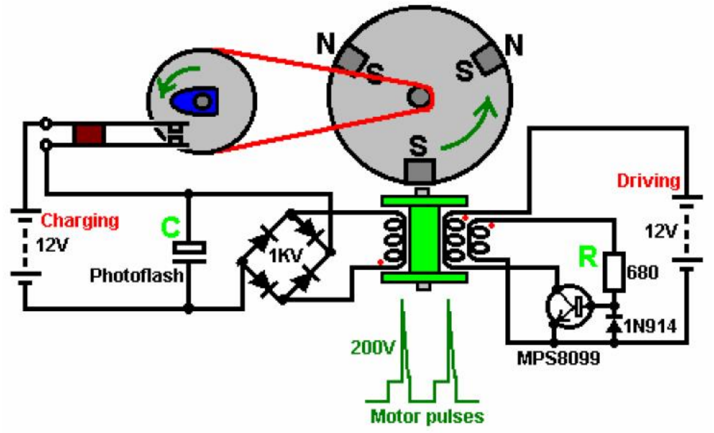

Figure 2. John Bedini's Battery-Charging System [35]

The operating principle and device comprise a motor wheel/disk (rotor), which has permanent magnets fastened on it. The disk rotates in front of a circuit coil (more precisely, a bi-filar wound transformer), performing a curvilinear alternating motion (accelerating/decelerating), which aims to create an induced current that will charge the battery. As the rotor passes over the circuit, it creates a changing magnetic field, which induces some charging current. Because the movement of the rotor is repetitive, i.e., it has a periodicity, pulses of a certain frequency and duration are produced.

Bedini has produced a whole series of similar designs [10], as well as other inventors like Ron Pugh [36]. The differences between these devices include:

- the number and size of rotors (disks);
- the number, size and position of the permanent magnets that can be fastened either on the rotor's rim (as in Fig. 2), or on its disk's periphery or even in concentric circles around its center (depending on the diameter of the rotor);
- the number and size of the picking coils (and/or transformers) that their position is dictated by the position of the corresponding permanent magnets;
- the composition and implementation details of the control circuit.

Naturally, the different configurations affect the features of the pulses, as presented above, and therefore the features of pulse-charging.

3.5. Simulation models

Batteries come in various shapes, sizes, and chemistries. Each type of lithium-ion battery exhibits unique characteristics influenced by factors such as electrode materials, electrolyte composition, and cell design. By employing simulation models tailored to specific battery types, we can capture the nuanced behavior of these energy storage devices under different charging conditions. Also, the complexity of battery behavior demands a deep exploration of the charging process. Simulation models enable us to dissect the electrochemical and thermal phenomena occurring within the battery during charging. This level of insight is crucial for identifying optimal charging parameters, understanding limitations, and predicting potential issues such as overheating or degradation. Furthermore, the use of simulation models allows us to explore a wide range of charging strategies efficiently. In the realm of lithium-ion batteries, where one size does not fit all, it's paramount to evaluate how different charging algorithms perform across diverse battery chemistries and configurations. Simulation provides a cost-effective and time-efficient platform for conducting these extensive studies.

In essence, simulation models empower us to bridge the gap between theoretical understanding and practical application. They offer a virtual laboratory where we can test and refine charging algorithms without the constraints of physical experiments. This iterative process accelerates the development of robust charging techniques, paving the way for enhanced battery performance, longevity, and safety. Thus, it is necessary to emphasize the critical role of simulation models in advancing our understanding of charging algorithms for lithium-ion batteries. As we delve into the intricacies of battery technology and seek to optimize charging techniques, the need for accurate and comprehensive simulation models becomes increasingly evident.

Different approaches are also used by previous works that form different simulation models, both linear and non-linear, to study different fast battery charging profiles [37]. Also, by using a battery simulation model and a battery health simulation model, mostly for automotive battery applications [38], there is a research effort to create an optimization framework to address the tradeoffs between charging time and life cycle time and degradation. There are also some studies on using deep learning methods on simulating the different battery chemistries and charging techniques, mostly based on CC/CV algorithms [39, 40].

4. Conclusion

Summarizing the experimental results, comparing both the proposed pulse-charging algorithm and the CC/CV charging algorithm as a reference, it has been demonstrated that the proposed pulse-charging algorithm, which transits from a high charging duty cycle (fast charging phase) to a low charging duty cycle (slow charging phase), to account for the increased polarization voltage of the battery, performs significantly better than CC/CV charging. Regarding the charging time, the proposed pulse-charging algorithm charged 100mAh and 45mAh lithium-ion batteries in 52 and 76 minutes, while using the CC/CV charging algorithm the batteries where fully charged in 83 and 90 minutes, respectively. This represented a reduction in charging time by 37.35% and 15.56% for the 100mAh and 45mAh batteries. The battery charging efficiency also improved by 3.15% and 3.27%, when using the proposed pulse-charging algorithm. Pulse charging at frequencies other than the optimal f_{Zmin} resulted in poor charging performance, especially for the 45mAh battery. As for the charging time, the proposed pulse charging algorithm resulted in faster charging times compared to the CC/CV charging algorithm at all measured frequencies. This indicates that for fast charging, the pulse-charging algorithm can be used, as the rest periods between pulses allow for effective ion movement and prevention of dendrite formation. However, for better battery charging performance, the pulse-charging algorithm should operate at f_{Zmin}. Last but not least, the rise of the temperature of the batteries used during pulse-charging was negative in both cases, compared to a small rise evidenced in CC/CV. That represents a less battery stress during charging, leading to a healthier charging cycle for the batteries and longer life cycle.

Regarding the pulse-charging of lead-acid and NiCad batteries, via voltage spikes, in order to obtain optimal pulse-charging current parameters and also to determine their impact on battery performance, optimization techniques should be used. One way to determine these optimal parameters is to try all possible combinations, but this will increase the manufacturing cost and consume time.

Therefore, the future direction of the related research may focus on the following points suggested:

- It is important to use the above-mentioned optimization techniques to determine which parameters and pulse charge current levels have the greatest effect on output performance metrics.
- At the same time, it is also important to predict pulse performance when it comes to build quality variability between batteries.
- Charts of pulse-charging methods can be designed for mapping optimization techniques and parameters to different types of batteries and, probably, related applications.

The above research directions may result in improving the energy efficiency of battery charging and, consequently, in a more sustainable usage of batteries, with less energy required and less waste disposed.

Declarations

Source of Funding

This research does not benefit from grant from any non-profit, public or commercial funding agency.

Competing Interests Statement

The authors have declared that no competing financial, professional or personal interests exist.

Consent for publication

All authors contributed to the manuscript and consented to the publication of this research work.

Acknowledgments

The authors express their thankfulness to the University of West Attica for supporting the publication of the results (through ELKE).

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