An Overview of the Fundamentals of Battery Chargers

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***Abstract*— This paper presents an overview of the fundamentals of battery chargers, including charging algorithms and circuit implementation of linear and switching battery chargers. First, the basic operation of batteries is described under open circuit, discharging, and charging conditions. Next, an overview of the pulse charging scheme and its implementation is presented, followed by an overview of the Constant-Current Constant-Voltage (CCCV) charging scheme and the special considerations pertaining to charging Lithium Ion (Li-Ion) batteries. Linear and switching circuit realizations of the CCCV charging scheme are then presented, followed by an overview of battery fuel-gauging circuits, multi cell chargers, and cell-balancing techniques.**

I. INTRODUCTION

Battery-operated devices have become an integral element of modern life. This includes, for example, communication and navigation devices, remotely deployed sensors, and portable multi-media players. In such devices, it is more practical and cost-effective to use rechargeable battery cells in order to avoid frequent replacement of batteries. As a result, battery chargers play an important role in the power management system of such devices. Charging a battery involves the charging algorithm, i.e. the procedure by which the battery is charged, and the circuit implementation of the algorithm. In this paper, a brief description of the most common battery charger implementations is presented.

II. BASIC OPERATION OF RECHARGEABLE BATTERIES

A battery converts chemical energy into electrical energy through a reduction-oxidation (redox) process between its active elements. These elements are the anode, the cathode, and the electrolyte, where the anode and the cathode serve as the negative and positive electrodes respectively, while the electrolyte serves as the shared medium in which the redox process takes place as shown in Fig. 1. The redox process results in the accumulation of negative charges on the anode terminal, causing its electric potential to become negative. Since the system is originally neutral, corresponding positive charges (cations) accumulate in the surrounding electrolyte medium, which creates an electric field between the electrolyte and the anode that opposes the redox process. Similar mechanism occurs at the cathode side, where positive charges accumulate on the cathode terminal, causing its electric potential to become positive. During open circuit conditions (i.e. no current flow between the battery terminals), and once the redox and electric forces at the anode and the cathode sides arrive to an equilibrium state, the potential difference between the cathode and the anode is what is referred to as the open circuit voltage of the battery [1].

During discharging conditions (i.e. the battery is loaded as shown in Fig. 1(a)), charge flows between the anode and the

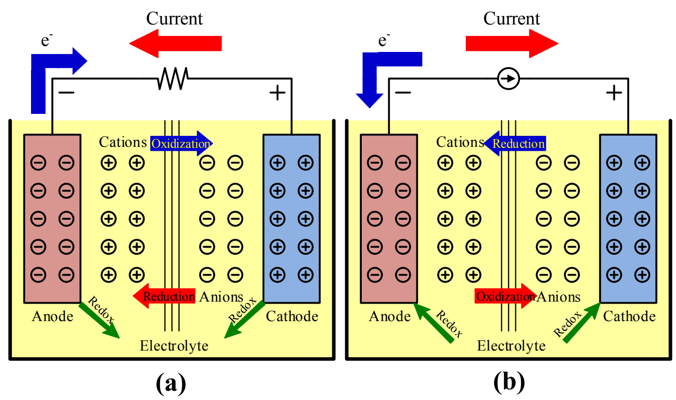

Fig. 1. A battery cell under (a) discharging, and (b) charging conditions.

cathode of the battery through the load, which disturbs the open circuit equilibrium state until a new equilibrium state is reached where the redox process continuously replenishes the charge consumed by the load. Ideally, this new equilibrium state should maintain the voltage across the battery to be the same as in the open circuit conditions. However, due to the finite time-constant of the redox process, the voltage across the battery in discharging conditions is lower than the open circuit case. Moreover, as discharging continues, the battery voltage drops until the battery is completely depleted [2].

During charging conditions, charge is injected into the battery as shown in Fig. 1(b). On the one hand, if the redox process is reversible (i.e. the battery is rechargeable), the injected charge is absorbed and stored by the battery. In this case, the battery is referred to as a secondary cell. On the other hand, if the redox process is irreversible (i.e. the battery is non-rechargeable), the injected energy is dissipated in the form of heat and the battery will eventually explode. In this case, the battery is referred to as a primary cell.

There are four parameters used to describe a battery: the state of charge (SoC), the capacity (C), the nominal voltage (V_{nom}), and the rated maximum voltage (V_{max}). SoC describes the battery status and is represented in percentage, where 100% describes a fully-charged battery and 0% describes a fully-depleted battery. C describes the maximum charge a battery can supply to a load from a fully-charged state to a fully-depleted state. Although C represents charge, it is usually measured in amp-hours (Ah) rather than Coulomb. Moreover, it is common to describe charging and discharging currents of a battery in terms of C rather than amps. V_{nom} is defined as the battery's average voltage as it is discharged with a constant current from a fully-charged state to a fully-depleted state, while V_{max} describes the maximum voltage the battery can produce when it is fully-charged.

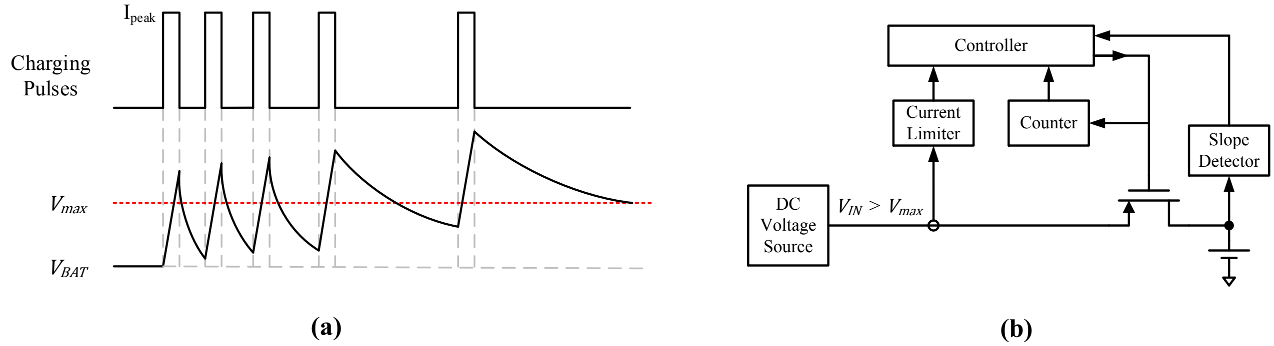

Fig. 2. The pulse-charging scheme: (a) transient behavior, and (b) block diagram showing the main components of a pulse charger.

III. Battery Charging Schemes

The process by which a battery is charged is referred to as the charging scheme. There are two common schemes for charging a battery: the pulse charging scheme, and the Constant-Current Constant-Voltage (CCCV) scheme [3].

A. The Pulse Charging Scheme

In the pulse charging scheme, a short, high-peak constant-current pulse is applied to the battery. Due to the high current level, the battery voltage initially spikes above the battery's rated maximum voltage until the battery is able to fully absorb the injected charge, after which the battery voltage recovers and settles to a slightly higher voltage than before the current pulse was applied as shown in Fig. 2(a). Once the battery voltage settles, another current pulse is applied, and the entire process is repeated. The period of time it takes the battery voltage to recover and settle after a current pulse is a strong function of the SoC of the battery, i.e. it takes much longer to recover when the battery is fully charged than if the battery is depleted. Thus, by observing the density of the applied current pulses, the SoC of the battery can be determined and the charging process can be stopped accordingly.

The pulse charging scheme is quite popular due to its simple and cost-effective implementation. Pulse chargers typically employ a power switch, a current-limiter, a slope detector, and a counter as shown in Fig. 2(b). The power switch is inserted between the battery and a DC voltage source that produces a slightly higher voltage than the rated maximum voltage of the battery. By turning ON the switch for a brief period, a short circuit condition is created between the voltage source and the battery, which causes a large current spike to flow into the battery. The level of the current pulse can then be limited by a current-limiter, which realizes the constant-current pulse needed to charge the battery. Since most DC voltage sources already have current limiting capability anyway, a separate current-limiter can often times be eliminated, which further reduces the cost of the charger. By using a slope detector to sense the settling of the battery voltage after a current pulse, along with a counter to count the density of the pulses, the full charger can be implemented.

However, pulse chargers have major disadvantages due to the high-peak current pulses and the spikes in the battery voltage associated with that. Although the spike in the battery voltage beyond the rated maximum voltage of the battery can be tolerated in certain types of batteries, such as lead acid, it cannot be tolerated in other types of batteries. For instance, since Li-Ion batteries are highly sensitive to voltage and temperature overload, the spike in the battery voltage and the excessive heat generated due to the high-peak current pulses is quite hazardous and can damage the battery, cause it to explode or catch on fire. Thus, the pulse charging scheme is highly undesirable for Li-Ion batteries and other well-controlled charging schemes must be used instead.

B. The Constatnt-Current Constant-Voltage (CCCV) Scheme

The CCCV charging scheme consists mainly of three phases as depicted in Fig. 3. The first phase, referred to as the trickle-charge phase, is used to test whether the battery is functioning properly or if it is damaged. This is achieved by applying a constant charging current to the battery for a preset period and observing the slope of the battery voltage. The constant current level used in this phase is normally limited to about $(1/10)$ the full charging current (I_{fc}) of the battery to avoid excessive heating if the battery is damaged. Once it is determined that the battery is responding as expected to the applied current, i.e. a healthy battery, the second charging phase is started. Otherwise, the charging process is terminated. In the second phase, referred to as the constant-current phase, the level of the charging current applied to the battery is increased to its full level, and the battery voltage is observed. This phase continues until the battery voltage reaches its rated maximum level, which typically corresponds to about 70% battery capacity. In order to reach 100% capacity, continuing the constant-current phase causes the battery voltage to increase beyond its rated maximum level, which damages the battery and causes excessive heating. Therefore, the constant-current phase must be stopped and the third phase is started. In the third phase, referred to as the constant-voltage phase, a constant voltage (equal to the rated maximum voltage of the battery) is applied across the battery while the battery current is observed. In this phase, the battery determines how much current it can absorb to continue the charging process. As the battery continues to charge further, its current starts to drop, and once the current drops to the trickle-charging level, i.e. $(I_{fc}/10)$, the constant-voltage phase is stopped and the battery is considered fully charged. It is worth mentioning that CCCV chargers can also

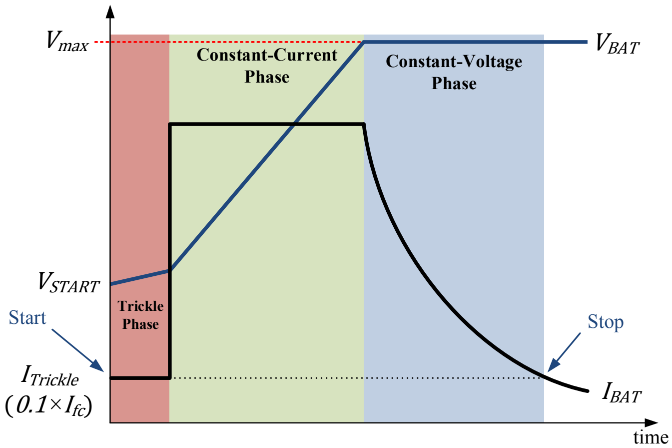

Fig. 3. The CCCV charging scheme showing the three main phases.

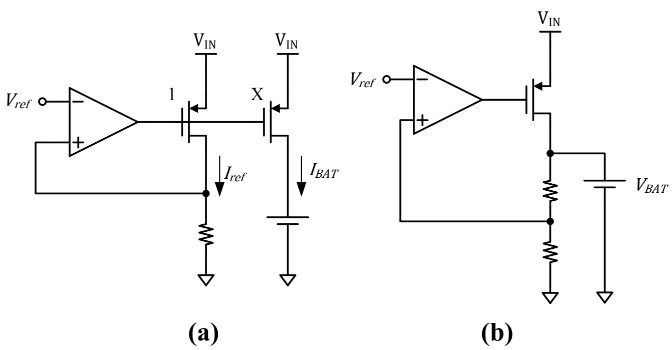

Fig. 4. Linear implementation of the CCCV charging scheme: (a) the constant-current phase, and (b) the constant voltage phase.

incorporate additional phases other than the three main phases described previously. In fact, some implementations add a constant-voltage phase, referred to as the top-off phase, after the battery is fully charged, and it is used only if the battery continues to be connected to a power source after it is fully charged. In this phase, the battery voltage is observed, and once it drops slightly below its rated maximum level (due to leakage or loading), a constant-voltage charging phase is activated for a brief period to ensure the battery is always fully charged if a power source is available. Moreover, some implementations add a constant-current phase, referred to as the short-circuit phase right before the trickle-charge phase. In this phase, a very small test current is applied to the battery to ensure the battery is properly connected to the chargers [4]. Since the CCCV charging scheme accurately controls the charging current level, as well as the charging voltage level, it is a very popular charging scheme for batteries that are sensitive to voltage or current levels, such as Li-Ion batteries.

The CCCV charging scheme involves multiple phases, some of them require applying a constant current to the battery and others require applying a constant voltage. Thus, its implementation is more complex than pulse charges. CCCV chargers can be implemented using simple linear current and voltage sources such as the ones shown in Fig. 4.

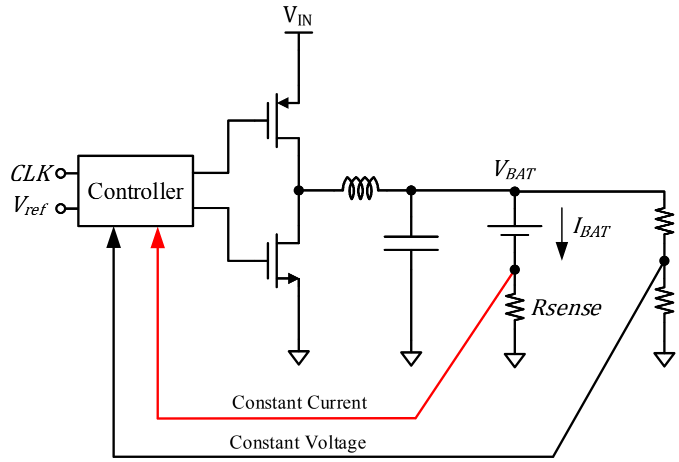

Fig. 5. Switching implementation of the CCCV charging scheme using a single buck converter for the constant-current and constant-voltage phases.

Since these sources have very similar design, they can share the same power transistor, which further reduces silicon area [5]. Although linear implementations are rather simple, they suffer from poor efficiency. This leads to higher heat generation and reduces the amount of charge that can be delivered to the battery from limited-current energy sources such as USB, which results in longer charging time. Alternatively, CCCV chargers can be implemented using efficient switching current and voltage sources as shown in Fig. 5. In this case, the current and voltage sources are implemented using a shared buck converter topology [4]. Switching implementations have the advantage of generating less heat and maximizing the charge that can be delivered to the battery from energy-limited sources. However, they tend to be bulky and more expensive due to the passive components required for the buck converter, and can cause Electromagnetic Interference (EMI) issues due to switching.

IV. Battery Fuel-Gauging

An important aspect of battery chargers is fuel gauging, which is necessary for estimating the SoC of the battery and how much charge is left in it [6]. Several techniques can be used for battery fuel gauging, such as measuring the battery internal impedance [7], observing the battery terminal voltage and internal impedance [8], and heuristic interpretation of discharge curves, e.g. coup de fouet technique [9]. However, the most common technique in portable devices is coulomb counting [10, 11], which relies on starting from a known SoC and battery capacity, and measuring the total charge consumed afterwards in order to estimate how much charge is left in the battery. A popular implementation of a coulomb counter is shown in Fig. 6, where the battery current is sensed using a sense resistor, then integrated linearly over time to estimate the total charge consumed from the battery [12]. Although such implementation is simple, there are some considerations that must be taken into account, such as the effect of integrator offset and flicker noise. These can introduce significant errors in the measured charge, and therefore, it is quite common to employ offset and flicker noise cancellation techniques, such as chopping and noise

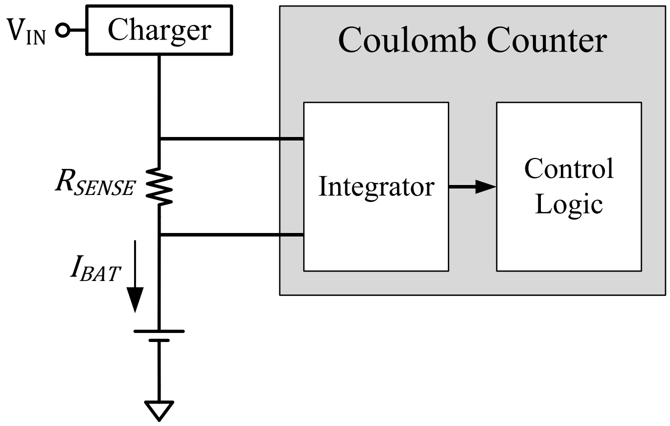

Fig. 6. A block diagram of a coulomb counter for battery fuel-gauging.

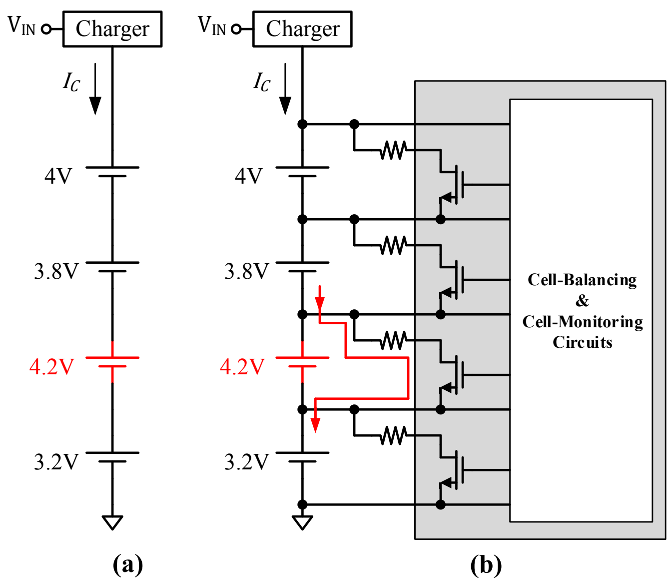

Fig. 7. (a) Charging a series stack of batteries with different time constants, (b) Cell-balancing and monitoring for routing the charging current.

shaping. However, coulomb counters have the limitation of requiring an initially known SoC and battery capacity. Thus, if the battery is taken offline then reinserted, the fuel-gauging results will be inaccurate until the battery goes through a full charging cycle first. Moreover, since battery capacity changes as the battery ages, updating its capacity may be necessary.

V. Multi-Cell Battery Chargers

Many applications require an energy source with higher voltage than what a single battery cell can provide. In this case, using a stack of multi cells in series is quite common. However, the process of charging multiple cells connected in series tends to be more complicated than charging a single battery cell. The reason behind that can be explained using Fig. 7(a), where multiple batteries are charged in the constant-current phase. Due to the variability in the charging time constant, each battery cell responds differently to the charging current, and therefore, the time needed for each cell to reach its rated maximum voltage is different. Continuing to charge the stack once one of the cells reaches its rated maximum voltage causes excessive heating and can damage this particular cell, while terminating the charging process entails that the stack will not be fully charged. In order to circumvent this problem, cell-balancing and cell-monitoring circuits are needed as shown in Fig 7(b) [13]. In this case, the voltage of each individual cell in the stack is independently monitored, and once any cell reaches its rated maximum voltage, the charging current is routed around the cell using a regulated current path composed of a current-limiting resistor and a power transistor. This way, the charging process can continue until all cells reach their rated maximum voltage without compromising the safety of each individual cell.

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