AN947

Power Management in Portable Applications: Charging Lithium-Ion/Lithium-Polymer Batteries

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INTRODUCTION

Powering today's portable world poses many challenges for system designers. The use of batteries as a prime power source is on the rise. As a result, a burden has been placed on the system designer to create sophisticated systems utilizing the battery's full potential.

Each application is unique, but one common theme rings true: ***maximize battery capacity usage***. This theme directly relates to how energy is properly restored to rechargeable batteries. While no single method is ideal for all battery chemistries, an understanding of the charging characteristics of the battery, along with the application's requirements, is essential when designing an appropriate and reliable battery-charging system. Each method has its associated advantages and disadvantages, with the particular application (and its individual requirements) determining the best method to use.

This application note focuses on the fundamentals of charging Lithium-Ion/Lithium-Polymer batteries. In particular, a linear, stand-alone solution utilizing Microchip's MCP73841 will be explored.

BATTERY OVERVIEW

A battery is a device that converts the chemical energy contained in its active materials directly into electric energy by means of an electrochemical oxidation-reduction (redox) reaction. This type of reaction involves the transfer of electrons from one material to another through an electric circuit. In a non-electrochemical redox reaction, such as rusting or burning, the transfer of electrons occurs directly and only heat is involved.

The operation of a battery during discharge is depicted schematically in Figure 1. When the electrodes (positive and negative terminals of the battery) are connected to an external load, electrons flow from the anode, which is oxidized, through the external load to the cathode. The cathode accepts the electrons and the cathode material is reduced. The electric circuit is completed in the electrolyte by the flow of anions (negative ions) and cations (positive ions) to the anode and cathode, respectively. By definition, the **cathode** (oxidizing electrode) is the electrode that accepts electrons from the external circuit and is reduced during the electrochemical reaction. The **anode** (reducing electrode) is the electrode which gives up electrons to the external circuit and is oxidized during the electrochemical reaction. The **electrolyte** (ionic conductor) provides the medium for transfer of charge, as ions, inside the battery between the anode and cathode.

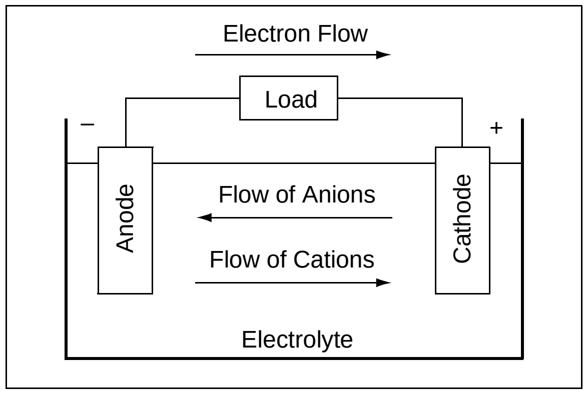

FIGURE 1: *Discharge of a Battery.*

When recharging a battery, the current flow is reversed, with oxidation occurring at the positive electrode and reduction at the negative electrode. As the anode is, by definition, the electrode at which oxidation occurs and the cathode where reduction occurs, the positive electrode is now the anode and the negative electrode is the cathode. Refer to Figure 2.

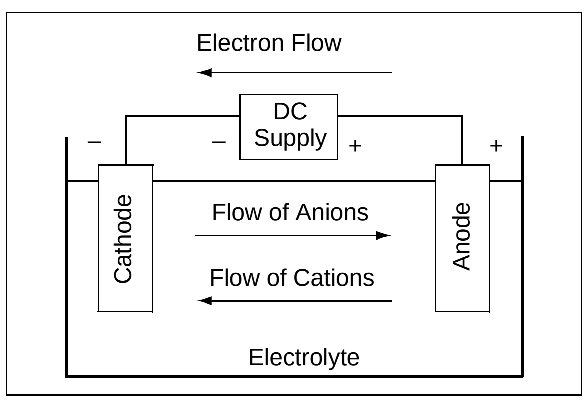

FIGURE 2: *Charge of a Battery.*

The standard potential of a battery is determined by the type of active materials contained in the battery. It can be calculated from free-energy data or obtained experimentally. The standard potential of a battery can be calculated from the standard electrode potentials as follows (the oxidation potential is the negative value of the reduction potential):

Anode (oxidation potential)
+ Cathode (reduction potential)
Standard Potential

For example, in a NiCd battery:

Cathode:

$2NiOOH + 2H_2O + 2e$ ---- $2Ni(OH)_2 + 2OH^-$ = 0.52V

Anode:

$Cd + 2OH^-$ ---- $Cd(OH)_2 + 2e$ = -0.81V

Standard Potential:

0.52 – (-0.81) = 1.33V

The theoretical capacity of a battery is determined by the amount of active materials in the battery. It is expressed as the total quantity of electricity involved in the electrochemical reaction and is defined in terms of coulombs (C) or ampere-hours (Ah). The ampere-hour capacity of a battery is directly associated with the quantity of electricity obtained from the active materials. Theoretically, 1 gram equivalent weight of material will deliver 96,487C or 26.8 Ah. (A gram equivalent weight is the atomic or molecular weight of the active material in grams divided by the number of electrons involved in the reaction.) The capacity of a battery can also be considered on an energy (watthour) basis by taking both the voltage and the quantity of electricity into consideration. This theoretical energy value is the maximum value that can be delivered by a specific electrochemical system.

The maximum energy that can be delivered by an electrochemical system is based on the types of active materials that are used (this determines the voltage) and the amount of active materials that are used (this determines the ampere-hour capacity). In practice, only a fraction of the theoretical energy of the battery is realized. This is due to the need for the electrolyte and non-reactive components (containers, separators, seals, etc.) that add to the weight and volume of the battery.

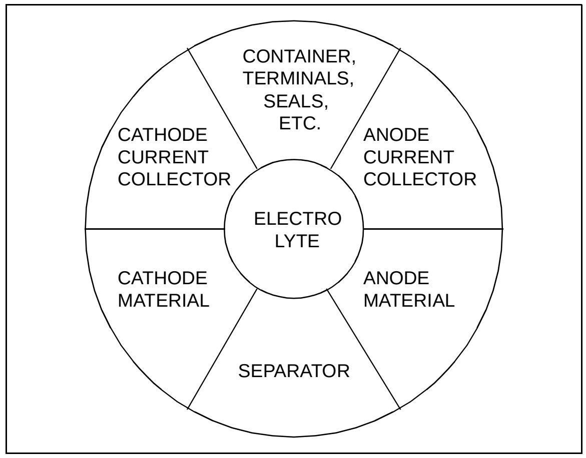

FIGURE 3: *Components of a Battery.*

The weight of the materials of construction reduces the theoretical energy density of the battery by almost 50%, with the actual energy delivered by a practical battery (even when discharged under conditions close to optimum) possibly being 50% to 75% of that lowered value.Thus, the actual energy available from a battery under practical discharge conditions is only about 25% to 35% of the theoretical energy of the active materials.

Referring to Figure 4, the theoretical voltage of a battery, as defined previously, is equivalent to the open-circuit voltage of a fully charged battery. When an electrical circuit is connected around the battery, with current being drawn from the battery, the closed-circuit voltage potential will be lower than the open-circuit voltage. This is due to two factors:

1. The electrodes have “real” impedance.
2. The rate at which current can be drawn from the battery is restricted by the rate at which the chemical reaction occurs. This looks like “resistance” to the electrical circuit and can be modeled as resistance in series with the cathode.

The nominal voltage is the voltage at the “plateau” of the discharge curve. For NiCd and NiMH batteries, the nominal voltage is 1.2V. For a Lithium-Ion battery, the nominal voltage is 3.6V. The end voltage is defined by the system and is the potential at which the system no longer draws current from the battery. The discharge cut-off voltage is a secondary safety potential, below which the battery can experience irrepairable damage.

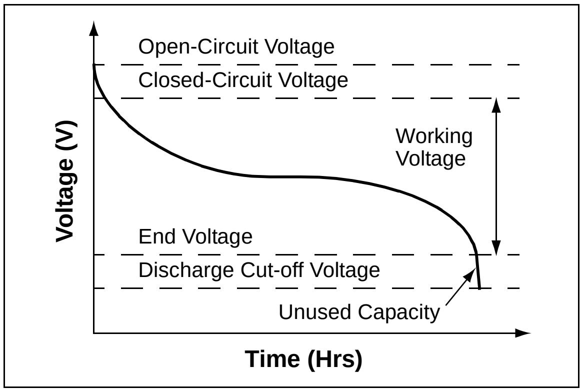

FIGURE 4: Battery Voltage Definitions.

When charging or discharging, the rate of charge or discharge is often expressed in relation to the capacity of the battery. This rate is known as the C-rate. The C-rate equates to a charge or discharge current and is defined as:

$$I = M \times C_n$$

Where:

I = charge or discharge current, A
M = multiple or fraction of C
C = numerical value of rated capacity, Ah
n = time in hours at which C is declared

A battery discharging at a C-rate of 1 will deliver its nominally-rated capacity in one hour. For example, if the rated capacity is 1000 mAh, a discharge rate of 1C corresponds to a discharge current of 1000 mA. A rate of C/10 corresponds to a discharge current of 100 mA.

Typically, manufacturers specify the capacity of a battery at 5 hour rate, n = 5. For example, the above mentioned battery would provide 5 hours of operating time when discharged at a constant current of 200 mA. In theory, the battery would provide 1 hour of operating time when discharged at a constant current of 1000 mA. In practice, however, the operating time will be less than 1 hour due to inefficiencies in the discharge cycle.

BATTERY TYPES

Batteries can be divided into two main categories: primary cells and secondary cells. Table 1 gives examples of primary and secondary cells.

TABLE 1: BATTERY TYPES

Primary Cells	Secondary Cells
Zinc Carbon	Sealed Lead Acid
Alkaline	Nickel Cadmium
Lithium	Nickel Metal-Hydride
	Lithium-Ion
	Lithium-Polymer

Primary cells produce an irreversible chemical reaction. Zinc Carbon batteries were the first introduced. The carbon was later purified to increase the energy capacity. These cells are more readily known as Zinc Chloride. Alkaline batteries are commonly found on store shelves and are widely used in disposable applications. Silver coin cell or button cell batteries are lithium batteries comprised of lithium metal and, since their chemical reaction is irreversible, are categorized as primary cells. Primary cells generally do not need built-in intelligence. Their disposable nature means that there is no need for recharge control, protection circuitry or “fuel” gauging.

Secondary cells are rechargeable by passing a current through them in the direction opposite to that of its discharge and reversing the chemical reaction. The most common forms of secondary cells include Sealed Lead Acid, Nickel Cadmium, Nickel Metal-Hydride, Lithium-Ion and Lithium-Polymer. Lead Acid batteries are typically used in automotive applications or fixed installations because of their large size and weight. Our focus will be discussing Lithium-Ion. These batteries have been emerging as the dominate chemistry in the portable market place.

LITHIUM-ION BATTERIES

Lithium-Ion batteries are comprised of cells that employ lithium intercalation compounds as the positive and negative materials. The positive electrode material is typically a metal oxide with either a layered structure (such as lithium cobalt oxide ($LiCoO_2$)) or a tunneled structure (such as lithium manganese oxide ($LiMn_2O_4$)) on a current-collector of aluminum foil. The negative electrode material is typically a graphite carbon on a copper current-collector.

The first Lithium-Ion batteries to be marketed (and the majority of those currently available) utilize lithium cobalt oxide as the positive electrode. This material offers good electrical performance, is easily prepared, has good safety properties and is relatively insensitive to process variation and moisture. More recently, lower-cost (lithium manganese oxide) or higher performance materials, such as lithium nickel cobalt oxide ($LiNiXCo_1$-XO_2), have been introduced, permitting development of batteries with improved performance. The first Lithium-Ion batteries employed cells with coke negative electrode materials. As better quality graphite became available, the industry shifted to graphite carbons as negative electrode materials because of their higher specific capacity, with improved life and rate capability. Until 1990, NiCd batteries dominated the portable, rechargeable market. Environmental concerns led to the development of NiMH and Lithium-Ion batteries. Lithium is the lightest metal in the periodic system and features the greatest electrochemical potential.

One of the biggest advantages of Lithium-Ion batteries is their superior energy density by weight and volume. Additionally, Lithium-Ion batteries do not exhibit the "memory" effect associated with the nickel-based batteries. Lithium-Ion batteries are, therefore, low maintenance. In other words, they do not need to be cycled periodically in order to maintain capacity. Of the three main types of portable, rechargeable batteries, Lithium-Ion exhibits the lowest self-discharge.

A drawback to Lithium-Ion is that it is in its relative infancy, resulting in higher costs. Also, Lithium-Ion batteries lose potential capacity even when not in use. In other words, Lithium-Ion batteries are subject to aging. Lithium-Ion batteries have a relatively high internal resistance, excluding them from high-discharge current applications, such as portable power tools. The high internal resistance is compounded by the added protection circuitry required by Lithium-Ion battery packs.

Why do Lithium-Ion battery packs need protection circuitry? The main reason is consumer safety. Excessive charging of Lithium-Ion cells can result in sudden, automatic and rapid disassembly. This is the Achilles' heel of Lithium-Ion cells. Conversely, excessive discharging of Lithium-Ion cells can decompose the anode, causing copper shunts to form. This causes permanent degradation of cell performance.

All Lithium-Ion battery packs, including single cells, employ protection circuitry in order to meet UL1642 and IEC Secondary Lithium Battery Standards. The protection circuitry consists of added electronics in series with the cell electrodes. The protection circuitry is composed of two MOSFETs connected in either a common drain or common source configuration. In batteries with 2 or more cells in series, P-channel MOSFETs are generally employed in series with the positive electrode. In single-cell batteries, N-channel MOSFETs are generally employed in series with the negative electrode. This protection should be viewed as the second, or last line, of defense. The battery charger should ensure that this protection is not utilized during normal operating conditions.

The operating range of a Lithium-Ion battery is between 4.2V and 2.8V. The internal safety protection circuits are designed to inhibit operation beyond this window, with the main goal of maintaining consumer safety. Therefore, protection against over-charge is its primary function. However, the protection circuitry often protects against undervoltage and excessive current. The primary goal of these protections is to maintain reliability, as opposed to safety. Refer to Figure 5 for a more detailed description.

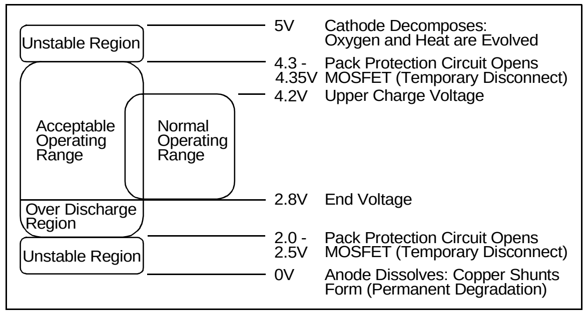

FIGURE 5: *Lithium-Ion Voltage Range.*

Lithium-Ion Charging Algorithms

So how is energy properly restored to a Lithium-Ion battery? The preferred charge algorithm for Lithium-Ion battery chemistries is a constant or controlled current; constant-voltage algorithm that can be broken up into three stages: trickle charge, fast or bulk charge and constant voltage. Refer to Figure 6.

Stage 1: Trickle Charge - Trickle charge is employed to restore charge to deeply depleted cells. When the cell voltage is below approximately 2.8V, the cell is charged with a constant current of 0.1C maximum. An optional safety timer can be utilized to terminate the charge if the cell voltage has not risen above the trickle charge threshold in approximately 1 hour.

Stage 2: Fast Charge - Once the cell voltage has risen above the trickle charge threshold, the charge current is raised to perform fast charging. The fast charge current should be less than 1.0C. In linear chargers, the current is often ramped-up as the cell voltage rises in order to minimize heat dissipation in the pass element. An optional safety timer can be utilized to terminate the charge if no other termination has been reached in approximately 1.5 hours from the start of the fast charge stage (with a fast charge current of 1C).

Stage 3: Constant Voltage - Fast charge ends, and the Constant Voltage mode is initiated, when the cell voltage reaches 4.2V. In order to maximize performance, the voltage regulation tolerance should be better than ±1%. It is not recommended to continue to trickle charge Lithium-Ion batteries. Charging is typically terminated by one of two methods: minimum charge current or a timer (or a combination of the two). The minimum current approach monitors the charge current during the constant voltage stage and terminates the charge when the charge current diminishes below approximately 0.07C. The second method determines when the constant voltage stage is invoked. Charging continues for an additional two hours before being terminated.

Charging in this manner replenishes a deeply depleted battery in roughly 165 minutes.

Advanced chargers employ additional safety features. For example, charge is suspended if the cell temperature is outside a specified window, typically 0°C to 45°C.

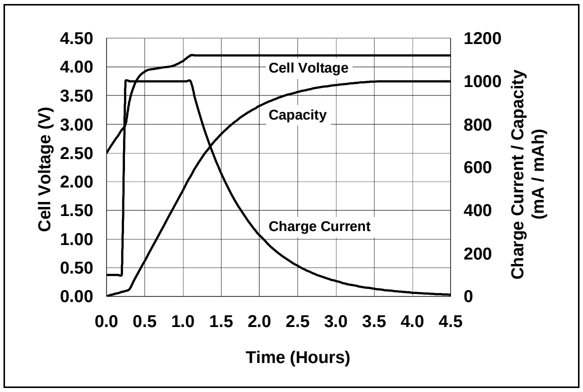

FIGURE 6: *Lithium-Ion Charge Profile.*

LITHIUM-ION CHARGING CONSIDERATIONS

A high-performance, fast battery charger is required to recharge any battery quickly and reliably. The following system parameters should be considered in order to ensure a reliable, cost-effective solution.

Input Source

Many applications use very inexpensive wall cubes as the input supply. Figure 7 depicts the schematic of a typical unregulated wall cube.

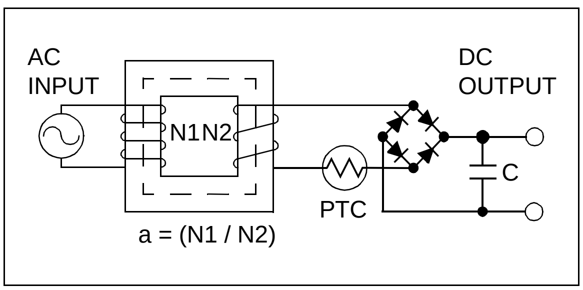

FIGURE 7: *Unregulated Wall Cube*

Due to its unregulated nature, the output voltage is highly dependent on the AC input voltage and the load current being drawn by the charger.

In the United States, the AC mains input voltage can vary from $90V_{RMS}$ to $132\ V_{RMS}$ for a standard wall outlet. Assuming a nominal input voltage of $120\ V_{RMS}$, the tolerance is +10%, –25%. The charger must provide proper regulation to the battery, independent of its input voltage. The input voltage to the charger will scale in accordance with the AC mains' voltage and charge current, assuming the output capacitance (C) is sufficiently large to minimize the voltage ripple:

$$V_O = \sqrt{2} \times V_{IN} \times a - I_O \times (R_{EQ} + R_{PTC}) - 2 \times V_{FD}$$

Where:

R_{EQ} = the resistance of the secondary winding plus the reflected resistance of the primary winding (R_P/ a^2)

R_{PTC}= the resistance of the PTC, and V_{FD} is the forward drop of the bridge rectifiers.

In addition, transformer core loss will slightly reduce the output voltage. Core loss is due to eddy current and hysteresis losses, and is effected by the area and permeability of the core, as well as the length of the closed magnetic path in the core.

The unregulated wall cube produces a typical DC output voltage to the charger, as shown in Figure 8.

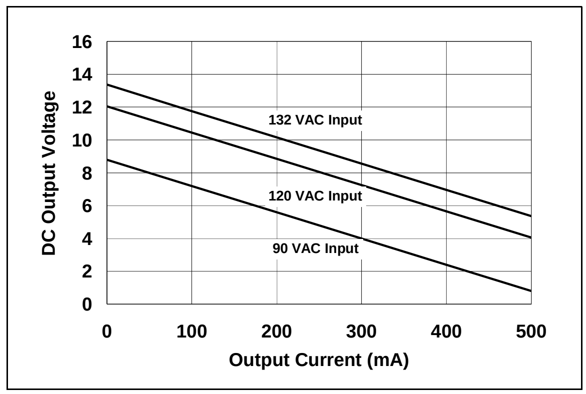

FIGURE 8: *Unregulated Wall Cube Output Voltage.*

Applications that charge from a car adapter can experience a similar problem. The pseudo-regulated car adapter output, depicted in Figure 9, is highly dependent on the input voltage and output current. At light loads, less than 20 mA, the car adapter operates in a discontinuous conduction mode and is regulated to approximately 8.2V. The duty cycle is dependent on the input voltage, output voltage, inductance and load. At outputs above 20 mA, the car adapter transitions to a continuous conduction mode. At this time, the output is unregulated. The duty cycle goes to the maximum, 50%. This is primarily due to the choice of the timing capacitor and the operation of the MC33063A. The output is roughly half the voltage seen at the switch emitter when Q_1 is on. The output varies slightly with load current due to losses in the current sense resistor (Q_1), the inductor and both diodes. Larger variations are seen in the output voltage due to the input voltage. Nominally, the input voltage is 12V – 12.5V when the car is not running and 14V – 14.5V when powered from the alternator. This corresponds to, roughly, a one volt change in output voltage.

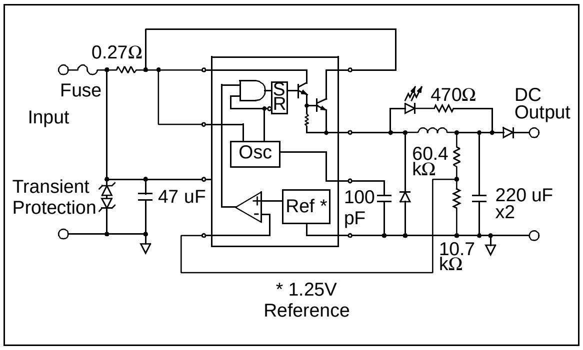

FIGURE 9: *Pseudo-regulated Car Adapter.*

As is, this adapter could not be used in many applications. A simple modification would allow the output to be regulated to 5V independent of input voltage or output current (there will be a slight dependence on output current because the regulation is being performed at the anode of the diode in series with the output). The modification can be performed by simply changing the value of the timing capacitor from 100 pF to 270 pF and changing the 10.7 kΩ resistor to 18 kΩ.

The pseudo-regulated car adapter produces a DC output voltage as shown in Figure 10. The simple modification mentioned increases the efficiency of the charging system, decreasing the heat generated in the handset.

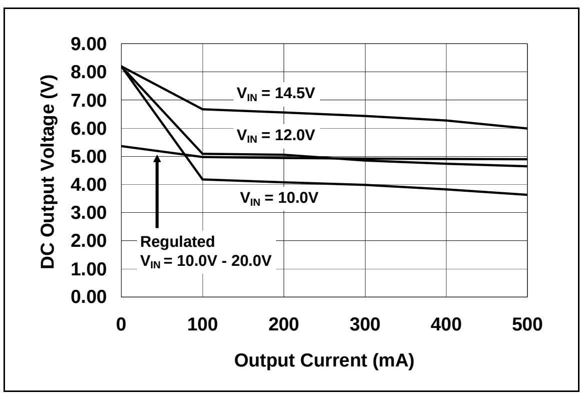

FIGURE 10: *Pseudo-regulated Car Adapter Output Voltage.*

Fast Charge Current and Accuracy

The choice of topology for a given application may be determined by the desired fast charge current. Many high fast charge current or multiple cell applications rely on a switch-mode charging solution for improved efficiency and less heat generation.

Linear solutions are desirable in low-to-moderate fast charge current applications for their superior size and cost considerations. However, a linear solution purposely dissipates excess power in the form of heat. Therefore, the tolerance on the fast charge current regulation becomes extremely important to a linear system. If the regulation tolerance is loose, pass transistors and other components will need to be oversized for a typical situation. In addition, if the fast charge current is low, the complete charge cycle will be extended. Refer to the **"Design Example"** section for details regarding the effects of fast charge current-regulation tolerance.

Output Voltage Regulation Accuracy

The output voltage regulation accuracy is critical in order to obtain the desired goal: ***maximize battery capacity usage***. A small decrease in output voltage accuracy results in a large decrease in capacity. However, the output voltage can not be set arbitrarily high because of safety and reliability concerns.

Figures 11 and 12 depict the importance of output voltage regulation accuracy.

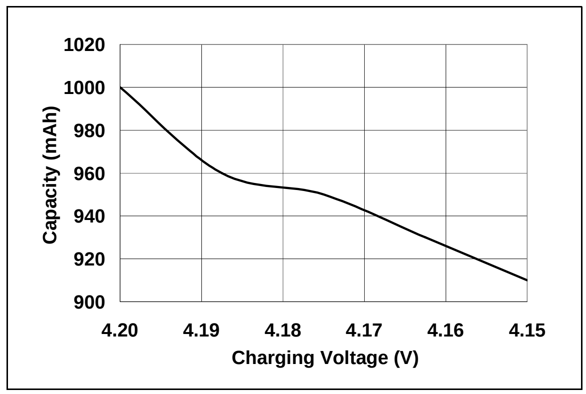

FIGURE 11: *Capacity vs. Charging Voltage.*

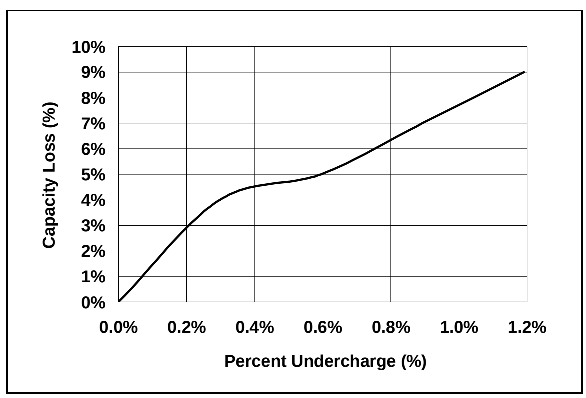

FIGURE 12: *Capacity Loss vs. Undercharge Voltage.*

Charge Termination Method

Primary and secondary charge termination methods are essential for reliably charging any battery chemistry. It can not be stressed enough that over-charging is the Achilles' heel of Lithium-Ion cells. The primary termination method for Lithium-Ion cells is determined by monitoring the charge current. After the constant voltage phase of the charge cycle has been entered, the charge current tapers off naturally. The charge cycle is considered complete when the charge current has diminished below the 0.1C to 0.07C rate. At this point, the charge cycle is terminated.

For a redundant secondary safety control, an elapsed charge timer should be utilized. If the battery does not reach full charge within a specified time, the charge cycle should be terminated. Continuing to charge may cause the battery to become hot, explode or ignite.

Cell Temperature Monitoring

The temperature range over which a Lithium-Ion battery can be charged is 0°C to 45°C, typically. Charging the battery at temperatures outside of this range may cause the battery to become hot. During a charge cycle, the pressure inside the battery increases, causing the battery to swell. Temperature and pressure are directly related. As the temperature rises, the pressure can become excessive. This can lead to a mechanical breakdown inside the battery or venting. Charging the battery outside of this temperature range may also harm the performance of the battery or reduce the battery's life expectance.

Generally, thermistors are included in Lithium-Ion battery packs in order to accurately measure the battery temperature. The charger measures the resistance value of the thermistor between the thermistor terminal and the negative terminal. Charging is inhibited when the resistance and, therefore, the temperature, is outside the specified operating range.

Battery Discharge Current or Reverse Leakage Current

In many applications, the charging system remains connected to the battery in the absence of input power. The charging system should minimize the current drain from the battery when input power is not present. The maximum current drain should be below a few microamps or, ideally, below one microamp.

DESIGN EXAMPLE

A practical design example will be presented along with actual charge-cycle waveforms.

The design parameters are given as follows:

Input Source:	5V, ±5%
Battery:	Single-cell, Lithium-Ion
Battery Capacity:	1000 mAh
Fast Charge Rate:	1C or 0.5C
Regulation Voltage:	4.2V
Primary Termination:	Imin
Secondary Termination:	Timer, 6 hours
Charging Temperature:	0°C to 45°C

Microchip's MCP73841-420I/MS was chosen as the preferred charge management controller because it satisfies all the given design parameters.

Device Overview

The MCP73841 is a highly advanced, linear charge-management controller. The MCP73841 utilizes an external pass transistor (MOSFET), thereby allowing great design flexibility and higher power (charging) levels. Figure 13 depicts the operational flow algorithm from charge initiation to completion and automatic recharge.

CHARGE QUALIFICATION AND PRECONDITIONING

Upon insertion of a battery or application of an external supply, the MCP73841 automatically performs a series of safety checks to qualify the charge. The input source voltage must be above the undervoltage lockout threshold, the Enable pin must be above the logic-high level, with the cell temperature monitor being within the upper and lower thresholds. These qualification parameters are continuously monitored, with any deviation beyond these limits automatically suspending or terminating the charge cycle.

Once the qualification parameters have been met, the MCP73841 initiates a charge cycle. The charge status output is pulled low throughout the charge cycle (see Table 2 for charge status outputs). If the battery voltage is below the preconditioning threshold (V_{PTH}), the MCP73841 preconditions the battery with a trickle-charge. The preconditioning current is set to approximately 10% of the fast charge regulation current. The preconditioning trickle-charge safely replenishes deeply depleted cells and minimizes heat dissipation in the external pass transistor during the initial charge cycle. If the battery voltage has not exceeded the preconditioning threshold before the preconditioning timer has expired, a fault is indicated and the charge cycle is terminated.

CONSTANT CURRENT REGULATION - FAST CHARGE

Preconditioning ends and fast charging begins when the battery voltage exceeds the preconditioning threshold. Fast charge regulates to a constant current (I_{REG}) based on the supply voltage minus the voltage at the SENSE input (V_{FCS}) developed by the drop across an external sense resistor (R_{SENSE}). Fast charge continues until either the battery voltage reaches the regulation voltage (V_{REG}) or the fast charge timer expires; In which case, a fault is indicated and the charge cycle is terminated. In this design example, V_{REG} equals 4.2V.

CONSTANT VOLTAGE REGULATION

When the battery voltage reaches the regulation voltage (V_{REG}), constant voltage regulation begins. The MCP73841 monitors the battery voltage at the V_{BAT} pin. This input is tied directly to the positive terminal of the battery.

CHARGE CYCLE COMPLETION AND AUTOMATIC RE-CHARGE

The MCP73841 monitors the charging current during the constant voltage regulation phase. The charge cycle is considered complete when the charge current has diminished below approximately 7% of the regulation current (I_{REG}) or the elapsed timer has expired.

The MCP73841 automatically begins a new charge cycle when the battery voltage falls below the recharge threshold (V_{RTH}) assuming all the qualification parameters are met.

CHARGE STATUS OUTPUT

A status output provides information on the state of the charge. The current-limited, open-drain output can be used to illuminate an external LED. Table 2 summarizes the state of the output during a charge cycle.

TABLE 2: STATUS OUTPUTS

Charge Cycle State	STAT1
Qualification	Off
Preconditioning	On
Constant Current Fast Charge	On
Constant Voltage	On
Charge Complete	Off
Safety Timer Fault	Flashing * (1Hz, 50% duty cycle)
Cell Temperature Invalid	Flashing * (1Hz, 50% duty cycle)
Disabled - Sleep mode	Off
Battery Disconnected	Off

***** The flashing rate (1 Hz) is based off a timer capacitor (C_{TIMER}) of 0.1 µF. The rate will vary depending on the value of the timer capacitor.

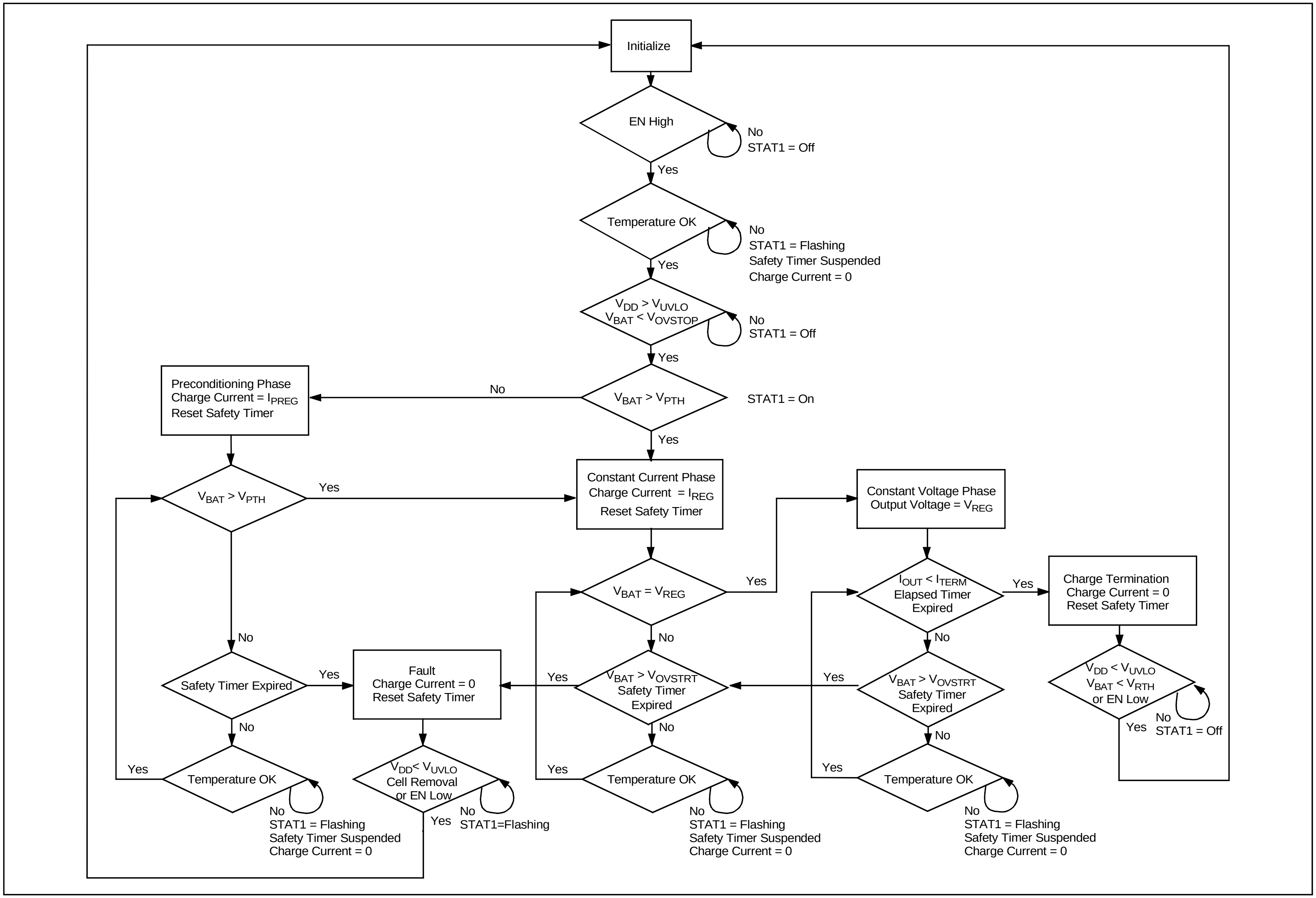

FIGURE 13: *MCP73841 Flow Algorithm.*

Circuit Design

Figure 14 illustrates the design circuit.

Due to the low efficiency of linear charging, the most important factors are thermal design and cost, which are a direct function of the input voltage, output current and thermal impedance between the external P-channel pass transistor and the ambient cooling air. The worst-case situation is when the device has transitioned from the preconditioning phase to the constant current phase. In this situation, the P-channel pass transistor has to dissipate the maximum power. A trade-off must be made between the charge current, cost and thermal requirements of the charger.

Component Selection

Selection of the external components is crucial to the integrity and reliability of the charging system. The following discussion is intended to be a guide for the component selection process.

SENSE RESISTOR

The preferred fast charge current for Lithium-Ion cells is at the 1C rate, with an absolute maximum current at the 2C rate. For this design example, the 1000 mAh battery pack has a preferred fast charge current of 1000 mA. Charging at this rate provides the shortest charge cycle times without degradation to the battery pack performance or life.

The current sense resistor, R_1, is calculated by:

EQUATION

$$R_1 = \frac{V_{FCS}}{I_{REG}}$$

Where:

I_{REG} is the desired fast charge current

A standard value 110 mΩ, 1% resistor provides a typical fast charge current of 1000 mA and a maximum fast charge current of 1091 mA. Worst-case power dissipation in the sense resistor is:

EQUATION

$$P_{R1} = 110m\Omega \times 1091mA^2 = 131mW$$

Two Panasonic® ERJ-3RQFR22V 220 mΩ, 1%, 1/8W resistors in parallel are more than sufficient for this application.

A larger-value sense resistor will decrease the fast charge current and power dissipation in both the sense resistor and external pass transistor, but will increase charge cycle times. Design trade-offs must be considered to minimize space while maintaining the desired performance. In this design example, fast charge rates of 1C and 0.5C have been compared. For a charge rate of 0.5C, one of the paralleled resistors was removed.

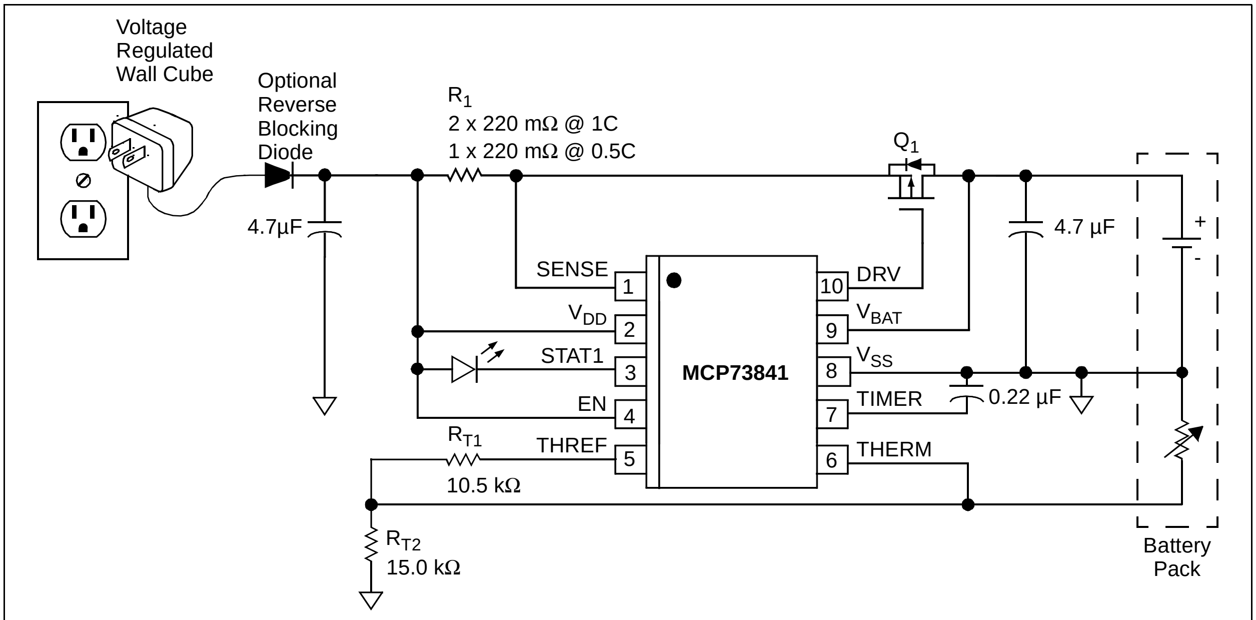

FIGURE 14: *Design Circuit.*

EXTERNAL PASS TRANSISTOR

The external P-channel MOSFET is determined by the gate-to-source threshold voltage, input voltage, output voltage and fast charge current. The selected P-channel MOSFET must satisfy the thermal and electrical design requirements.

Thermal Considerations

The worst-case power dissipation in the external pass transistor occurs when the input voltage is at the maximum and the device has transitioned from the preconditioning phase to the constant current phase. In this case, the power dissipation is:

EQUATION

$$P_{Q1} = (V_{DDMAX} - (V_{PTHMIN} + V_{FCS})) \times I_{REGMAX}$$

Where:

V_{DDMAX} is the maximum input voltage

I_{REGMAX} is the maximum fast charge current

V_{PTHMIN} is the minimum transition threshold voltage

Maximum power dissipation in this design example occurs when charging at the 1C rate.

EQUATION

$$P_{Q1} = (5.25V - (2.85V + 0.120)) \times 1091mA = 2.48W$$

Utilizing a Fairchild® NDS8434 or an International Rectifier IRF7404 mounted on a 1 in^2 pad of 2 oz. copper, the junction temperature rise is 99°C, approximately. This would allow for a maximum operating ambient temperature of 51°C.

By increasing the size of the copper pad, either a higher ambient temperature or a lower-value sense resistor could be utilized.

Alternatively, different package options can be utilized for more or less power dissipation. Again, design tradeoffs should be considered to minimize size while maintaining the desired performance.

Electrical Considerations

The gate-to-source threshold voltage and R_{DSON} of the external P-channel MOSFET must be considered in the design phase.

The worst-case V_{GS} provided by the controller occurs when the input voltage is at the minimum and the fast charge current regulation threshold is at the maximum.

The worst-case V_{GS} is:

EQUATION

$$V_{GS} = V_{DRVMAX} - (V_{DDMIN} - V_{FCSMAX})$$

Where:

V_{DRVMAX} is the maximum sink voltage at the V_{DRV} output

V_{DDMIN} is the minimum input voltage source

V_{FCSMAX} is the maximum fast charge current regulation threshold

Worst-case V_{GS} with a 5V, ±5% input voltage source and a maximum sink voltage of 1.0V is:

EQUATION

$$V_{GS} = 1.0V - (4.75V - 120mV) = -3.63V$$

At this worst-case V_{GS}, the R_{DSON} of the MOSFET must be low enough as to not impede the performance of the charging system. The maximum allowable R_{DSON} at the worst-case V_{GS} is:

EQUATION

$$R_{DSON} = \frac{V_{DDMIN} - V_{FCSMAX} - V_{BATMAX}}{I_{REGMAX}}$$

$$R_{DSON} = \frac{4.75V - 120mV - 4.221V}{1091mA} = 375m\Omega$$

The Fairchild NDS8434 and International Rectifier IRF7404 both satisfy these requirements.

External Capacitors

The MCP73841 is stable with or without a battery load. In order to maintain good AC stability in the Constant Voltage mode, a minimum capacitance of 4.7 µF is recommended to bypass the V_{BAT} pin to V_{SS}. This capacitance provides compensation when there is no battery load. In addition, the battery and interconnections appear inductive at high frequencies. These elements are in the control feedback loop during Constant Voltage mode. Therefore, the bypass capacitance may be necessary to compensate for the inductive nature of the battery pack.

Virtually any good quality output filter capacitor can be used, independent of the capacitor's minimum Effective Series Resistance (ESR) value. The actual value of the capacitor and its associated ESR depends on the forward transconductance, g_m, and capacitance of the external pass transistor. A 4.7 µF ceramic, tantalum, or aluminum electrolytic capacitor at the output is usually sufficient to ensure stability for up to a 1A output current.

REVERSE-BLOCKING PROTECTION

The optional reverse-blocking protection diode, illustrated in Figure 14, provides protection from a faulted or shorted input, or from a reversed-polarity input source. Without the protection diode, a faulted or shorted input would discharge the battery pack through the body diode of the external pass transistor.

If a reverse protection diode is incorporated in the design, it should be chosen to handle the fast charge current continuously at the maximum ambient temperature. In addition, the reverse-leakage current of the diode should be kept as small as possible. A Panasonic® MA2YD100L, 1.5A, 15V, Schottky diode has been chosen. The forward voltage drop is 350 mV at 1A, which is important when determining the maximum allowable R_{DSON} of the pass transistor. The reverse leakage of this diode is outstanding. With a reverse voltage of 4.0V, the leakage is less than 1 µA.

ENABLE INTERFACE

In the stand-alone configuration, the enable pin is generally tied to the input voltage. The MCP73841 automatically enters a low power mode when voltage on the V_{DD} input falls below the undervoltage lockout voltage (V_{STOP}) reducing the battery drain current to 0.23 µA, typically.

CHARGE STATUS INTERFACE

A status output provides information on the state-of-charge. The current-limited, open-drain output can be used to illuminate an external LED. Refer to Table 2 for a summary of the state of the status output during a charge cycle.

CELL TEMPERATURE MONITORING

The MCP73841 continuously monitors temperature by comparing the voltage between the THERM input and V_{SS} with the upper and lower comparator thresholds. A negative or positive temperature coefficient, NTC or PTC thermistor and an external voltage divider typically develop this voltage. The temperature-sensing circuit has its own reference to which it performs a ratio metric comparison. Therefore, it is immune to fluctuations in the supply input (V_{DD}). The temperature-sensing circuit is removed from the system when V_{DD} is not applied, eliminating additional discharge of the battery pack.

The design example specifies a charging temperature of 0°C to 45°C. A NTC thermistor with a 25°C resistance of 10 kΩ and a sensitivity index (β) of 3982 is inside the battery pack. The thermistor has a resistance of 33.56 kΩ at 0°C and 4.52 kΩ at 45°C. The values for resistors R_{T1} and R_{T2} are calculated with the following equations.

For NTC thermistors:

$$R_{T1} = \frac{2 \times R_{COLD} \times R_{HOT}}{R_{COLD} - R_{HOT}}$$

$$R_{T2} = \frac{2 \times R_{COLD} \times R_{HOT}}{R_{COLD} - 3 \times R_{HOT}}$$

Where:

R_{COLD} and R_{HOT} are the thermistor resistance values at the temperature window of interest

The calculated values for R_{T1} and R_{T2} are 10.44 kΩ and 15.17 kΩ, respectively. Standard values of 10.5 kΩ and 15.0 kΩ provide a temperature window within 1°C of that desired.

SAFETY TIMER

The TIMER input programs the period of the safety timers by placing a timing capacitor (C_{TIMER}) between the TIMER input pin and V_{SS}. Three safety timers are programmed via the timing capacitor.

The preconditioning safety timer period:

EQUATION

$$t_{PRECON} = \frac{C_{TIMER}}{0.1\mu F} \times 1.0 Hours$$

The fast charge safety timer period:

EQUATION

$$t_{FAST} = \frac{C_{TIMER}}{0.1\mu F} \times 1.5 Hours$$

And, the elapsed time termination period:

EQUATION

$$t_{TERM} = \frac{C_{TIMER}}{0.1\mu F} \times 3.0 Hours$$

The preconditioning timer starts after qualification and resets when the charge cycle transitions from preconditioning to the fast charge phase. The fast charge and elapsed timers start once the MCP73841 transitions from preconditioning. The fast charge timer resets when the charge cycle transitions to the constant voltage phase. The elapsed timer will expire and terminate the charge if the sensed current does not diminish below the termination threshold.

The design example specifies a charge termination time of six hours. A standard value 0.22 µF ceramic capacitor has been chosen.

Charge Cycle Waveforms

Figure 15 depicts complete charge cycles utilizing the MCP73841 with fast charge currents at the 1C and 0.5C rates. When charging at a rate of 0.5C instead of 1C, the same steps are performed. It takes about one hour longer to reach the end of charge. The MCP73841 scales the charge termination current proportionately with the fast charge current. The result is an increase of 36% in charge time, with the benefit of a 2% gain in capacity and reduced power dissipation. The change in termination current from 0.07C to 0.035C results in an increase in final capacity from ~98% to ~100%. The system designer has to make a trade-off between charge time, power dissipation and available capacity.

CONCLUSION

Properly restoring energy using the latest battery technology for today's portable products requires careful consideration. An understanding of the charging characteristics of the battery, as well as the application's requirements is essential in order to design an appropriate and reliable battery-charging system.

A stand-alone linear charging solution for Lithium-Ion/Lithium-Polymer batteries was presented. The guidelines and considerations presented herein should be taken into account when developing any battery charging system.

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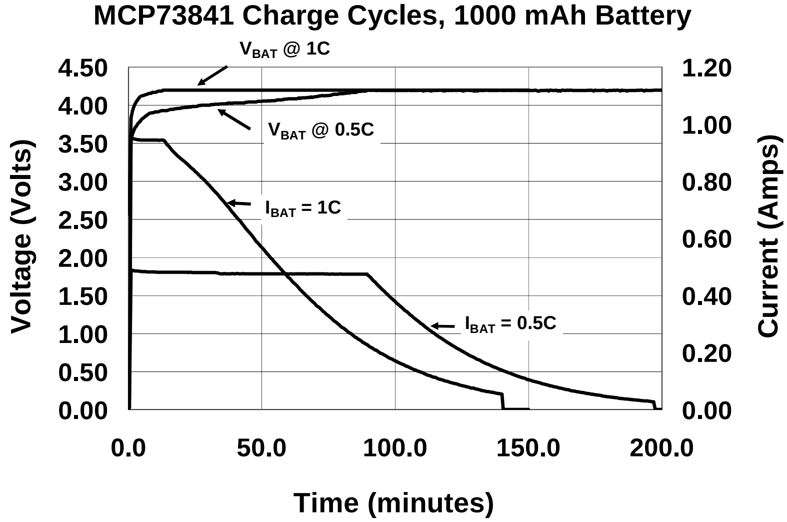

FIGURE 15: *MCP73841 Charge Cycle Waveforms.*

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