APPLICATION NOTE U-168

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Implementing A Practical Off-line Lithium-Ion Charger Using The UCC3809 Primary Side Controller And The UCC3956 Battery Charger Controller

UNITRODE

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By Eddy Wells

Introduction

A primary goal in the design of any portable electronic device is to make the product as small and lightweight as possible. When the device is powered by a rechargeable battery, a means of charging the battery from the AC line must be provided. Although battery charging is often thought of as a secondary function, the proper implementation of a charging system can ultimately determine the success of a product.

Off-line charger designs are often based on the use of a 60 Hz transformer; the magnetic is used to provide isolation and transform the line voltage to a lower level. The transformer's output voltage is rectified and fed into a DC/DC converter which provides charge current to the battery. Although this design approach is inherently simple, it can be bulky even at low power levels.

A steel 60Hz transformer used to deliver 10 watts, for example, weighs 0.5 pounds and occupies 5 cubic inches of volume. In contrast, a ferrite transformer at the same power level, operated at a 100kHz switching frequency, weighs only 0.02 pounds and has a volume of 0.25 cubic inches. This 20:1 reduction in size will allow the charger to reside in the portable device in most instances.

This paper will describe a 120VAC off-line charger that is based on a two series cell Lithium-Ion pack with a 1200mA hour capacity rating. The design described here can be modified to address different line and pack voltages. The paper will address the recommended charge algorithm for the pack, primary and secondary circuitry design, feedback loop compensation, and magnetic design for the converter.

Four-State Charge Algorithm for Lithium- Ion Batteries

Lithium-Ion batteries are becoming popular in portable and lap-top applications because of their superior energy density with respect to both weight and volume. Lithium-Ion batteries have higher cell voltages than the Nickel based chemistries they are replacing, averaging 3.6V per Lithium-Ion cell. Lithium-Ion batteries have safety concerns, however, and unique characteristics that require a dedicated charging algorithm. Figure 1 depicts the recommended fast charge algorithm for the two cell Lithium-Ion pack.

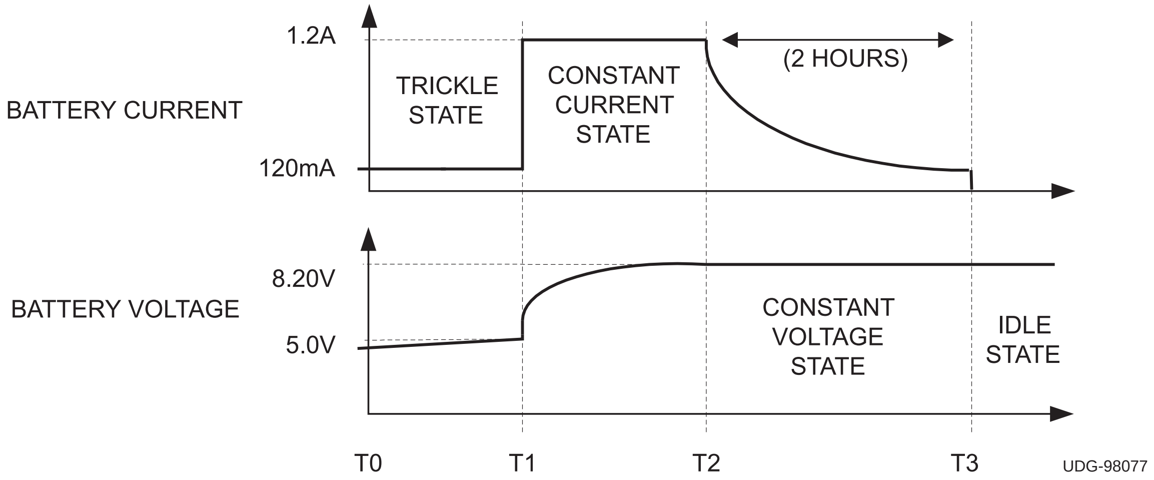

Figure 1. Recommended Charge Profile for Two Cell Lithium-Ion Battery Pack

Trickle State (t0-t1)

If the battery pack's voltage is below 5 volts, the pack is severely depleted and near zero capacity. Since the possibility of a shorted cell exists, the charger should not deliver full current to the battery. A reduced C/10 charge current of 120mA is applied to the cells in an attempt to safely restore capacity. In most cases, the battery will have some initial capacity and the charger will begin operation in the constant current state.

Constant Current State (t1-t2)

When the pack is above the 5 volt threshold, a constant current or "bulk" charge period will restore about 80% capacity to the cells. The current level of the charger will be set at 1.2A, corresponding to a 1C charge rate. The time period of the constant current state will depend on the battery's initial capacity.

Constant Voltage State (t2-t3)

When the pack reaches its final voltage (t2), constant voltage control is initiated, causing the battery current to decrease. Because Lithium-Ion batteries have safety concerns associated with the over-charging of cells, a timed constant voltage period is preferred by battery manufacturers[1][2]. The constant voltage period will regulate the pack to 8.2 volts (1% tolerance) for a duration of 2 hours. The timed constant voltage state will predictably restore the battery to 100% capacity.

Idle State

Once the timer expires (t3), the charge current to the pack is terminated and the fully charged pack is ready for use. The charger electronics will stay powered in the idle state, awaiting the start of a new charge cycle.

Design Overview

Figures 2 and 7 show a complete schematic for the 2 cell off-line charger. Since the peak output power of the charger is only 10 Watts, a flyback topology has been selected, requiring only a single magnetic component. The charger provides 3000 volts of isolation between the input line and battery in order to protect the user. This rating is determined by the optocoupler's pin spacing and transformer's insulation.

The primary side circuitry controls the peak current in the flyback transformer, while the average current delivered to the battery during the various charge states is programmed by the secondary side circuitry. An optocoupler is used to transfer the control signal from secondary to primary. The charger is designed to operate with discontinuous current, eliminating the need for slope compensation.

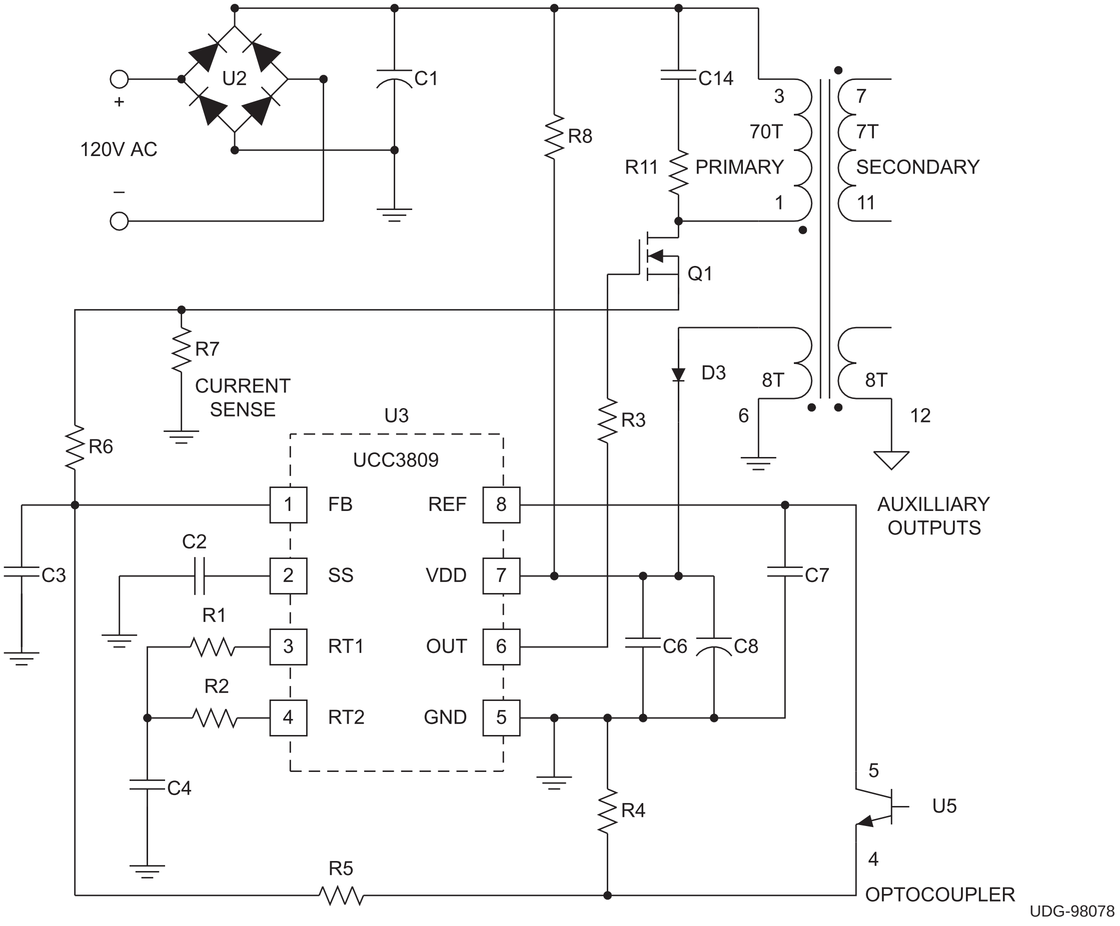

Figure 2. Primary Side Circuitry

Primary "Line" Side Operation

The charger operates off of a 120 volt line with a 10 percent tolerance. As shown in Figure 2, the line voltage is rectified and filtered by C1 to provide a DC voltage that can vary between 130 and 190 volts (depending on line and load conditions). The amount of 120Hz ripple at C1 is a function of the capacitance value selected and the power level of the charger(3). A 33µF capacitor results in a maximum ripple of 15V at 10 Watts. Peak voltage stress on Q1 is equal to the sum of the maximum input voltage (190V), the maximum secondary voltage reflected by the turns ratio (9V x 10 = 90V), and the voltage spike created by leakage inductance in the transformer. A dissipative snubber (R11 & C14), limits the leakage spike to 100V. A 500V MOSFET (IRF820) was selected for Q1. Figure 3 shows the voltage on the drain of Q1 at full and light loads, along with primary and secondary currents.

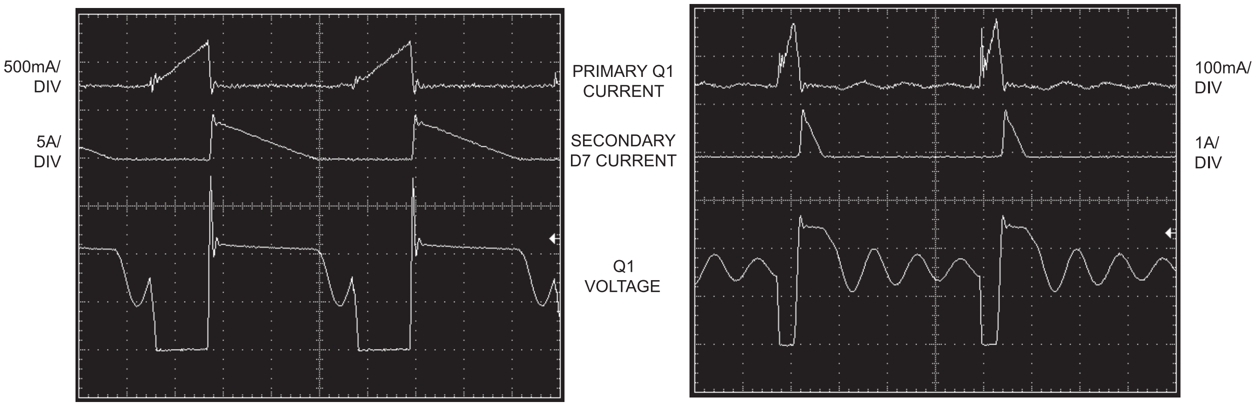

Figure 3. Q1 and D7 waveforms at Full and Light Loads

When line voltage is initially applied to the charger, power is supplied to the primary controller through R8 and an internal 17V zener. A bootstrap winding on the flyback transformer provides additional supply current to C8 through D3 once the converter powers up. The amount of supply energy needed for the primary side circuitry is primarily a function of the MOSFET's capacitance. With a switching frequency of 100kHz, a supply current of 15mA is sufficient.

Unitrode's UCC3809(4) provides peak current control for the charger. Peak current control has the advantage of providing pulse by pulse short circuit protection in the event the output is shorted at the battery. The frequency of operation (100kHz) and maximum duty cycle are set by the component values connected to the RT1 and RT2 pins, while the SS pin sets a soft-start period.

Referring to figure 4, at the beginning of a switching cycle Q1 is turned on and current ramps up in the primary winding of the transformer. This current forms a voltage across the current sense resistor (R7). The secondary side circuitry sets a DC voltage level at the emitter of the optocoupler (V_{OPTO})

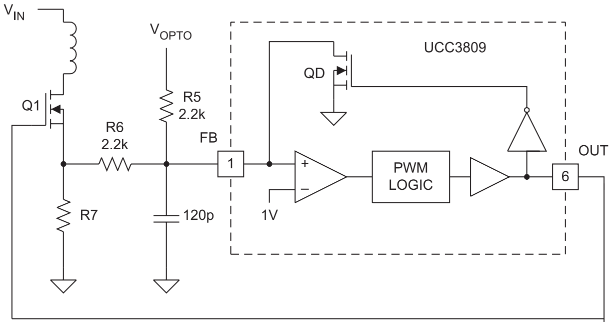

Figure 4. UCC3809 Peak Current Mode Control on Primary

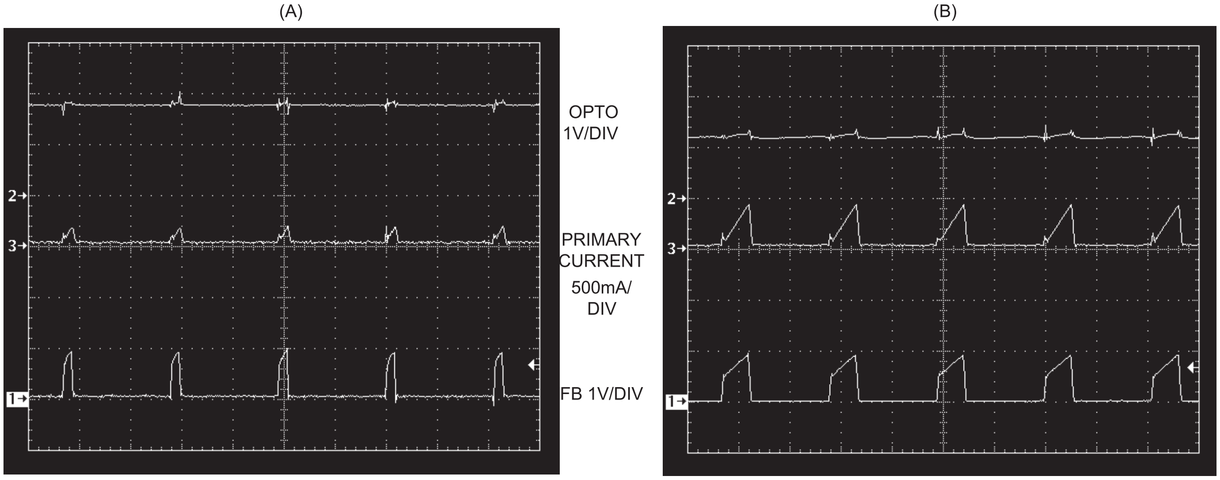

Figure 5. Light Load Operation (A), Full Load Operation (B)

that is used to control peak current ; when Vopto is decreased peak current will increase. The two voltages are summed into the FB pin of the primary controller through resistors R5 and R6. The FB pin is internally connected to the non-inverting input of a precision comparator, whose output turns Q1 off (via the OUT pin) when FB reaches 1 volt.

Switch Q_D, internal to the UCC3809, pulls the FB pin low when the OUT pin is low. With Q1 off, flyback current is forced out of the secondary winding and delivered to the battery. Figure 5 shows the operating voltages at the emitter of the optocoupler and the FB pin at light load and full load respectively, along with primary current.

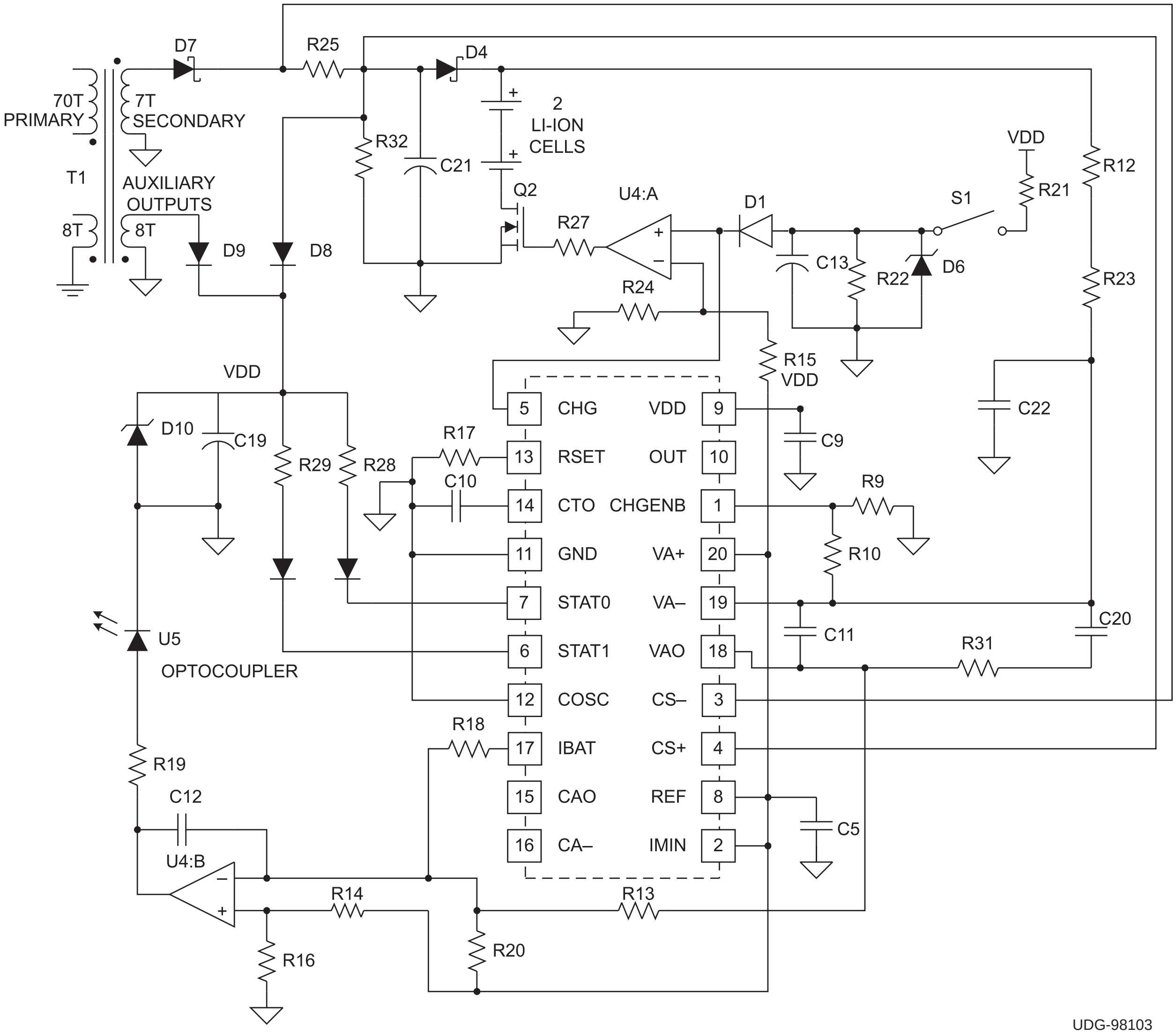

Figure 6. Secondary Side Circuitry

Secondary Side Operation

Secondary side control is provided by Unitrode's UCC3956 Lithium-Ion charger controller. The IC contains a precision 4.1V reference, an overcharge timer, and the control circuits necessary to implement the recommended charge profile of Figure 1. The controller has two status pins (STAT0, STAT1) which indicate the various states of the charger. A block diagram of the UCC3956 controller IC is shown if Figure 7 for reference.

The complete secondary side schematic for the charger is shown in Figure 6. Secondary current is sensed through R25, which is Kelvin connected to a current sense amplifier at pins CS- and CS+.

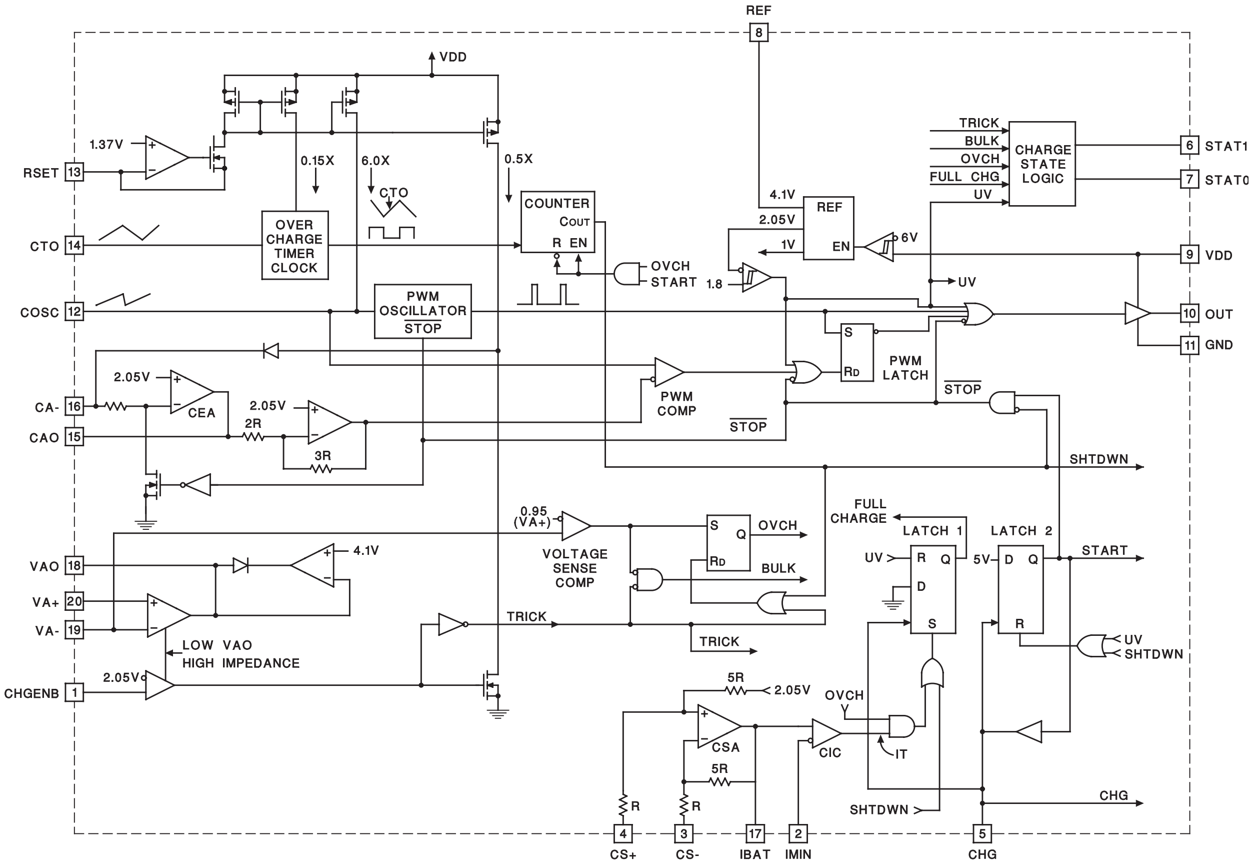

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Figure 7. UCC3956 Lithium-Ion Control IC

Programming the Trickle State. Referring to Figure 6, resistors R9, R10, R12, and R23 set the threshold voltage for trickle charge state at 5.0V (CHGEN pin).

$$V_{TRICKLE} = \frac{R9 + R10 + R12 + R23}{R9} \bullet 2.05 \tag{1}$$

When the battery voltage is below this level, the controller's voltage amplifier output (VAO) is put into a high impedance state. The average battery current is programmed to 120mA by a resistive divider between R20 (connected to Vref) and R18 (connected to the output of the current sense amplifier at IBAT). The external error amplifier produces the appropriate command signal, which is transferred across the optocoupler to the primary.

$$I_{TRICKLE} = \frac{2.05 \bullet R18}{5 \bullet R20 \bullet R25} \text{ (Amps)} \tag{2}$$

Programming the Constant Current "Bulk" State. When battery voltage is between 5.0 and 8.20 volts, the constant current state is activated and the voltage amplifier is internally clamped to 4.1 volts. The average battery current is set at 1.2A by a resistive divider, R18 and R13 between the output of the current sense amplifier and the voltage amplifier.

$$I_{BULK} = \frac{2.05 \bullet R18}{5 \bullet R13 \bullet R25} \text{ (Amps)} \tag{3}$$

Programming the Constant Voltage State. The resistor divider used to set the trickle threshold, also sets the final pack voltage to 8.20 volts at the VA– pin.

$$V_{FINAL} = \frac{R9 + R10 + R12 + R23}{R9 + R10} \bullet 2.05 \tag{4}$$

During the overcharge state, the voltage amplifier comes into regulation and its output voltage decreases, causing the average battery current to decrease. The overcharge timer period is programmed to 2 hours with a 0.18µF capacitor on the CTO pin. When the charger completes the constant voltage state, a MOSFET in series with the battery is opened, preventing additional charge to the battery.

$$\text{Timeout} = 4500 \bullet R17 \bullet C10 \text{ (min)} \quad (5)$$

Keeping the Charger Powered. In order to keep the charger powered and intelligent during all modes of operation, a capacitor (C21) and dummy load (R32) are added across the output of the flyback secondary. When the charger is in the idle state (or when the battery is out of the charger) the controller regulates the dummy load to 8.2V plus a diode drop. An additional diode (D4), prevents the pack from discharging in the event the charger is unplugged from the line. An auxiliary winding, similar to the winding on the primary circuit, is used to power the secondary controller. An 18V Zener (D10) assures the controller's maximum voltage specification is not exceeded.

Controller Modifications

The UCC3956 is designed to be a stand-alone controller for a DC to DC buck converter, certain modifications are needed to accommodate the off-line flyback design.

1. Since the MOSFET Q1 is driven by the primary side controller, the PWM output pin (OUT) of the UCC3956 is not connected.
2. The controller's error amplifier (CA) is replaced with an external LM358 Op-Amp (U4:B). This modification is necessary since the UCC3956 disables its error amplifier when the charger is in the idle state and the off-line charger needs the amplifier to keep the dummy load in regulation.
3. The second Op-Amp in the LM358 package (U4:A) is configured as a comparator, which interfaces between a momentary push button switch, the CHG pin, and the MOSFET (Q2) in series with the battery pack as shown in Figure 8a. The momentary push switch (S1) is used to initiate a charge cycle. When S1 is closed, R21 and C13 provide a slowly rising voltage at the CHG pin as shown in the timing waveforms of Figure 8b. At time t1, the comparator turns Q2 on before the CHG pin recognizes a new charge cycle at time (t_2). This allows time for the output voltage (V_{OUT}) to collapse from the idle state voltage (8.5V) to the uncharged battery voltage, preventing the constant voltage state timer from being initiated prematurely. The charger then progresses through its normal charge algorithm programmed with the UCC3956 (t_3-t_4). At the completion of the charge cycle (t_5), the CHG pin pulls low, Q2 is opened, and the charge current to the battery is terminated. The charger then waits in the idle state for the initiation of a new charge cycle.

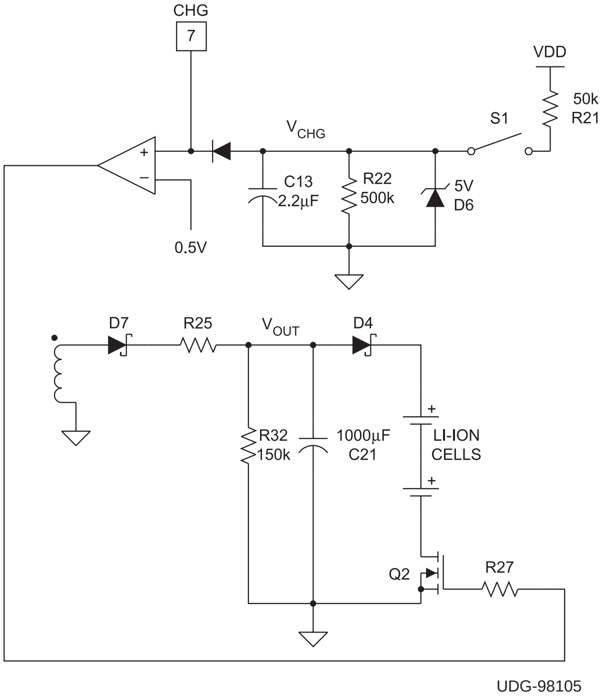

Figure 8a. CHG Pin Interface

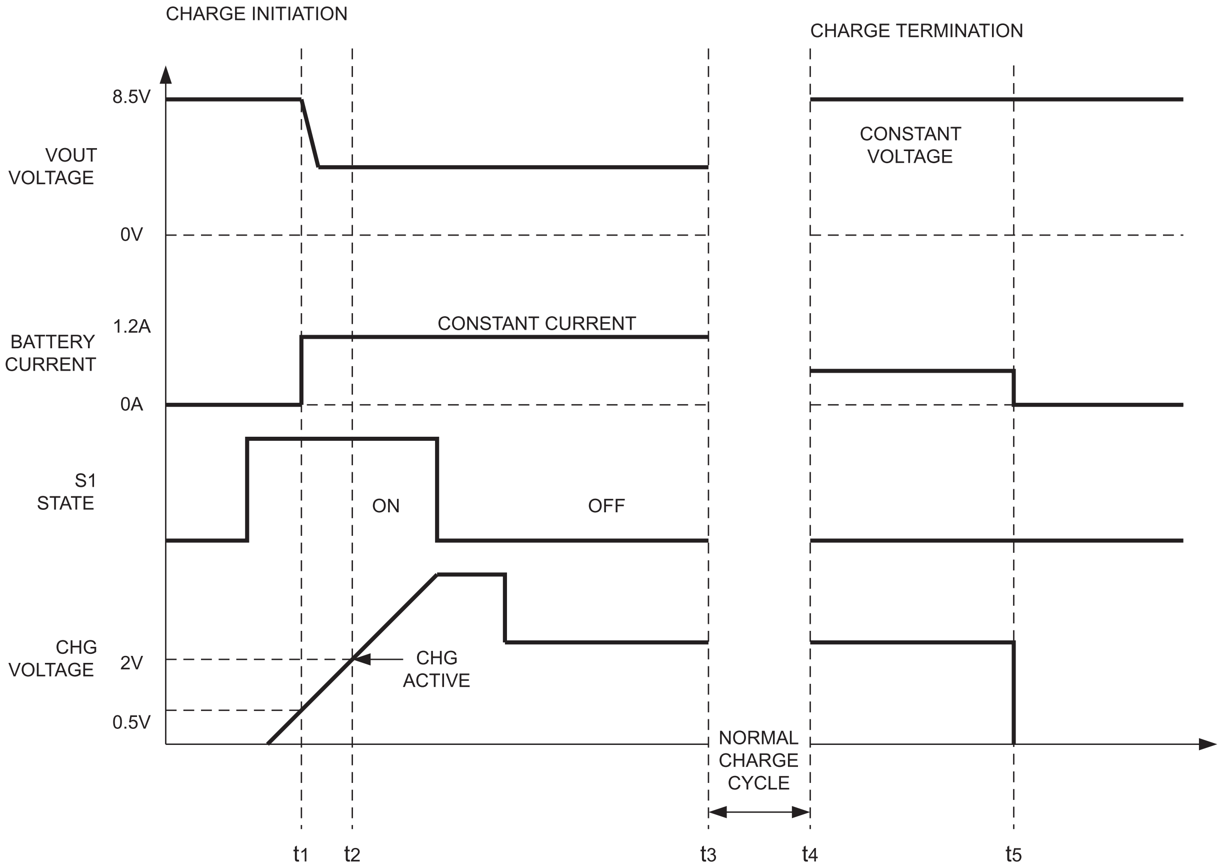

Figure 8b. CHG Pin Waveforms

Feedback Design

Figure 9 depicts the key elements that form the feedback network for the charger.

Referring to Figure 9, the battery current is sensed across R25 and amplified by the **current sense amplifier**. This signal is averaged by the **error amplifier**, and fed across the isolation barrier through the optocoupler circuit. The resulting voltage at the output of the optocoupler sets the peak current in the transformer primary. During the trickle and bulk charge states, the current loop takes exclusive control of the charger.

When the battery voltage approaches its final programmed value, the **voltage amplifier** comes into regulation and begins to reduce the current to the battery. The voltage loop maintains the battery voltage at 8.2V during the constant voltage period of operation. The voltage loop also regulates the dummy load voltage when the charger resides in the idle state.

Closing the Current Loop

A peak current control technique on the primary results in an uncompensated current loop gain that is essentially constant out to half the switching frequency. Referring to Figure 9, (and assuming equal values for R5 and R6) the small signal gain of the uncompensated current loop is determined by the primary sense resistor (1/R7), the transformer turns ratio (N), and the current sense amplifier circuit (5 • R25). Since the converter is run in discontinuous conduction mode, the gain is also a function of load. With the battery at 6 volts and 1.2 amps of bulk current, the current loop has a measured power stage gain of 4db. During trickle and overcharge periods, this loop gain is reduced as the current to the battery is reduced.

The optocoupler circuit adds an additional 5db of gain (R4/R19) to the power stage. The optocoupler has a pole around 50kHz, but this has minimal effect on phase margin, as the compensated current loop will cross unity gain at a much lower frequency.

As shown in Figure 9, the error amplifier is fed from the voltage and current sense amplifiers. When calculating the small signal gain of the current loop, the voltage amplifier output can be viewed as a DC source.

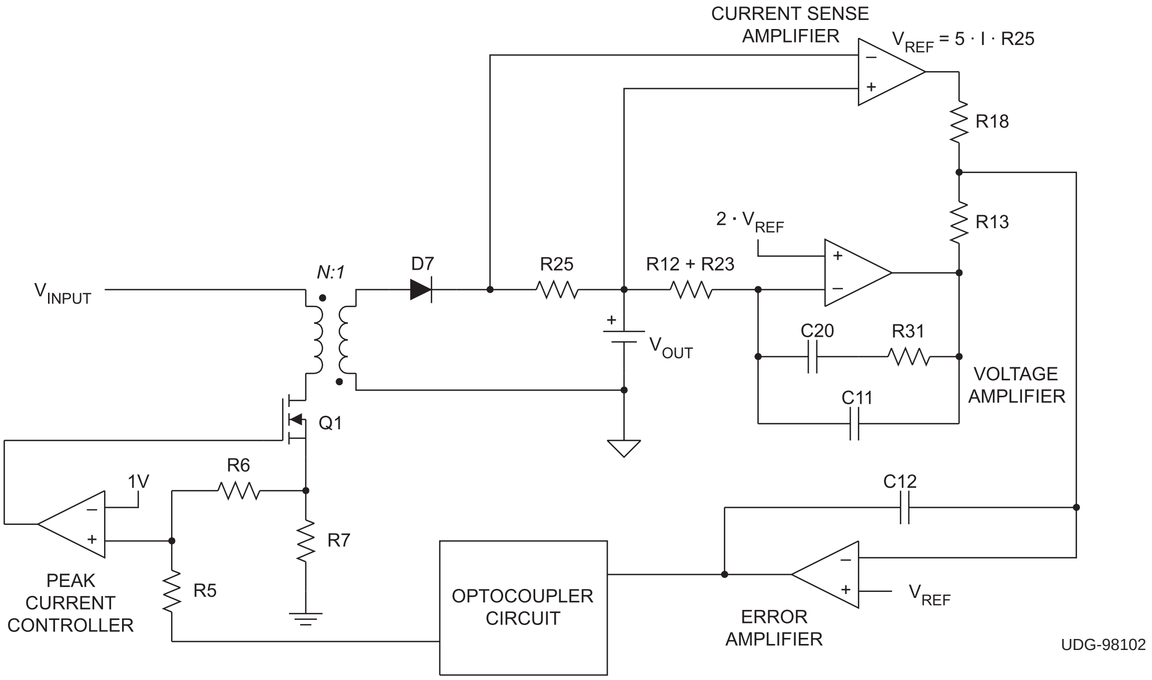

Figure 9. Simplified Charger Feedback Diagram

Single pole compensation (–20dB/decade) is added to the error amplifier to provide good dynamic response and stable operation. The gain of the error amplifier is equal to the impedance of the feedback capacitor C12 divided by R18. With C12 equal to 4700pF and R18 equal to 15K, the resulting cross over frequency is 2kHz (Figure 10, Error Amplifier). Adding the 9db of gain from the power stage and the optocoupler circuit (Figure 10. PWR + OPTO), the total current loop gain crosses unity gain around 6kHz (Figure 10. Total Loop).

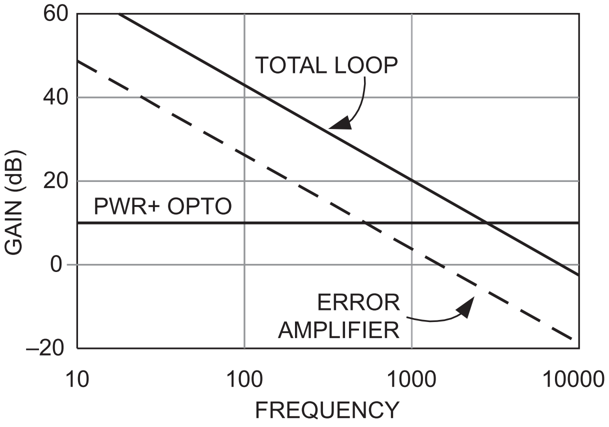

Figure 10. Current Loop Feedback

Adding the Voltage Loop

The gain of the voltage loop consists of the closed current loop gain 1/(5*R25) multiplied by the effective impedance of the output(6). The voltage amplifier's effect on the current loop is attenuated by the Thevenin network [R18/(R18+R13)].

Although an accurate frequency model for a battery can be complex, the frequency characteristics of the 2 cell pack can be approximated as a constant gain out to 200Hz with a single pole roll-off above 200Hz. When the charger is in the idle state, C31 and R32 form a single pole frequency response at 1Hz. Figure 11A depicts the uncompensated frequency responses of the battery and dummy load voltage loops.

Interactions with the current loop are avoided by designing the total voltage loop to cross unity gain around 500Hz. The frequency characteristics of the voltage amplifier's pole-zero-pole compensation network (R31, C11, C20) are shown in figure 11B. A low frequency pole gives a high gain at DC to produce an accurate final pack voltage. A zero is added near 20Hz to prevent the loop phase from reaching 180 degrees. A final pole is added near 1kHz to provide a high frequency noise filter.

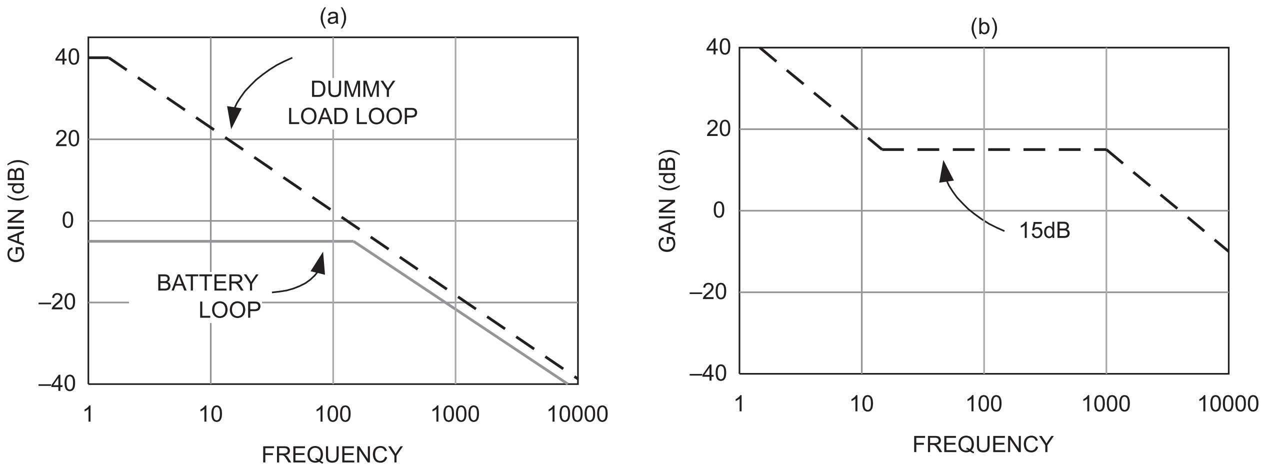

Figure 11. Voltage Feedback. (a) uncompensated voltage loop, (b) voltage amplifier compensation

Transformer Design

The first step in the design of the transformer is to determine the proper cross sectional area of the ferrite core (7). The required cross sectional area (A_C) of the core is based on the number of turns (N) and the maximum flux density (B_{MAX}) allowed before saturation.

$$V_{IN} \bullet T_{ON} = 4\,x\,10^{-4} \bullet B_{MAX} \bullet A_C \bullet N \tag{6}$$

According to Gauss' Law (equation 6) this occurs when the product of input voltage (V_{IN}) and on-time (T_{ON}) is at a maximum. The required winding area (Aw) of the bobbin is determined from the wire gauge and number of turns for the various windings. Since wire losses are resistive, RMS current should be used when calculating current density in the wires. An EDF20 core set made by Phillips provides adequate core and winding areas for the flyback transformer. The transformer has a small footprint, measuring 20mm per side. Coiltronics (407-241-7876) provided a custom transformer for the charger [Part Number - CTX08 13959].

Minimum inductance values are required on the primary and secondary windings, to assure that the charger always operates with discontinuous current. These inductance values are achieved by adding the proper air gap to the center leg of the flyback transformer's core. The Coiltronics transformer is gapped to give 165mH per 1000 turns (A_L). The transformer primary has 70 turns giving 800µH of primary inductance. The secondary inductance is related to the primary by $1/N^2$, giving 8µH of secondary inductance. Figure 12 illustrates the current in the flyback transformer during a switching period.

The charger operates at 100kHz, leaving 10µSec (T_{PERIOD}) for the primary inductance to charge to a peak current and the secondary inductance to discharge into the load. The converter approaches continuous current conduction when the input voltage and the battery voltage are at a minimum and when the converter is in the bulk charge state. In this state, the pack has a minimum of 5 volts and the transformer secondary will be clamped to 5V plus two diode drops during discharge ($V_{DISCHARGE}$). For an average battery current of 1.2A, the peak secondary current and discharge time can be determined by solving equation 7 and equation 8.

The secondary peak current is calculated to be 4A with a corresponding discharge time of 5.6µS. With 130V DC on the input capacitor, the maximum on-time is calculated to be 2.6µS. This leaves 1.8µS of discontinuous current margin for component variations.

$$I_{BATTERY\_AVERAGE} = \frac{T_{DISCHARGE}}{2 \bullet T_{PERIOD}} \bullet I_{PEAK\_SECONDARY} \tag{7}$$

$$V_{DISCHARGE} \bullet T_{DISCHARGE} = L_{SECONDARY} \bullet I_{PEAK\_SECONDARY} \tag{8}$$

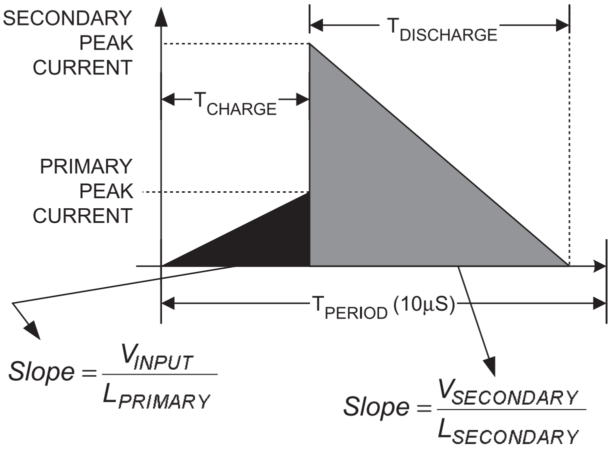

Figure 12. Flyback Transformer Current.

Summary

A high frequency off-line battery charger has been presented that offers a compact and lightweight solution when compared to a design based on a 60Hz transformer. By using dedicated ICs, parts count is minimized, increasing system reliability and reducing cost. The charger incorporates all of the features necessary to assure safety, long life, and rapid charging for Lithium-Ion cells. The final board measurements are shown in figure 13 along with component placement. A parts list for the charger is given in Table 1.

References

[1] M. Juzkow and C. St. Louis of Moli Energy, *Designing Lithium-Ion Batteries into Today's Portable Products.* Portable by Design Conference 1996

[2] P. Bennett and G. Braun of Energizer Power Systems, I*ntroduction to Applying Lithium-Ion Batteries*. Portable by Design Conference 1997

[3] Unitrode Corporation Power Supply Design Seminar 900, *Line input AC to DC Conversion and Input Filter Capacitor Selection*, topic I1.

[4] Unitrode Corporation Product Data Book (1997), *UCC1809 Economy Primary Side Controller.*

[5] Unitrode Corporation Product Data Book (1997), *UCC3956 Switch Mode Lithium-Ion Battery Charger Controller.*

[6]. Lloyd Dixon, Unitrode Corporation Power Supply Design Seminar 1100, *Control Loop Cookbook Appendix C.*

[7] Magnetics Ferrite Cores Catalog (1991), *Transformer Core Size Selection*, Page 4.3.

For more complete information, pin descriptions and specifications for the UCC3809 Primary Side Controller and the UCC3956 Battery Charger Controller see the UCC3809 and/or the UCC3956 data sheet or contact your Unitrode Field Applications Engineer at (603) 424–2410.

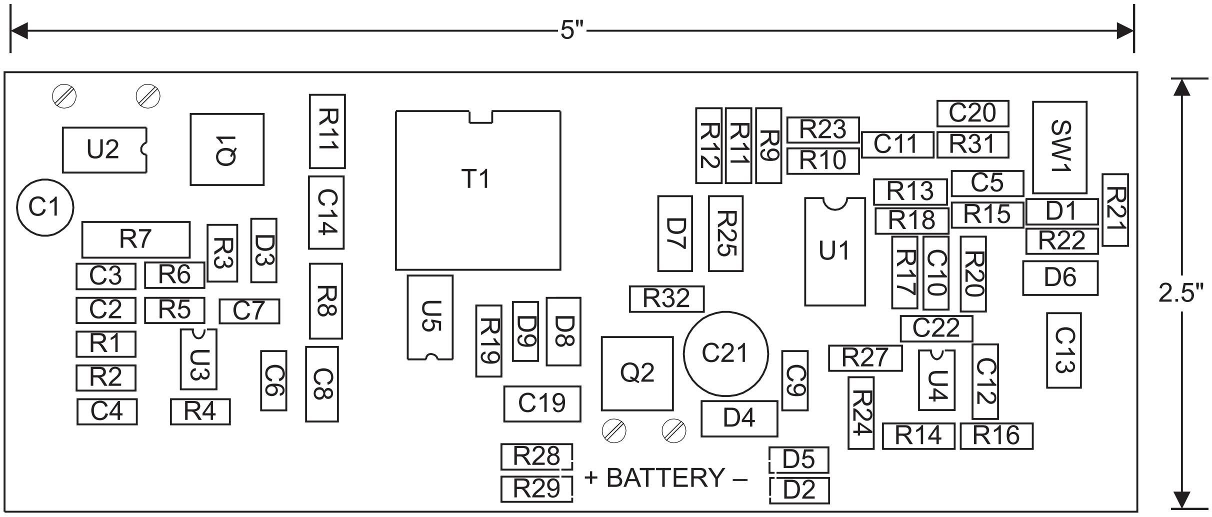

Figure 13. Final Board Size and Component Placement

Table 1. Charger Parts List

Reference Designator	Description	Manufacturer	Part Number
C1	33µF, 250V Aluminum Electrolytic Capacitor	Panasonic	ECA-2EM330
C2, C5, C6, C7, C9, C22	0.1µF, ceramic chip cap, 1206 package		
C3	120pF, ceramic chip cap, 1206 package		
C4	1000pF, ceramic chip cap, 1206 package		
C8	10µF, tantalum capacitor, C case size		
C10	0.18µF, ceramic chip cap, 1206 package		
C11	2200pF, ceramic chip cap, 1206 package		
C12	4700pF, ceramic chip cap, 1206 package		
C13	2.2µF, tantalum capacitor,		
C14	100µF, 500V Mica Capacitor		
C19	22µF, tantalum capacitor,		
C21	1000µF, 16V Aluminum Electrolytic Capacitor	Panasonic	ECE-A1CU102
D1,D3, D8, D9	General purpose diode, mini-melf package	Digikey	DL4148MSCT
D2, D5	SMD LEDs, 1206 package		
D4, D7	3A Schottky Diodes	General Instruments	SK34
D6	5V, 500mW, zener diode		
D10	18V zener diode		
Q1	Surface mount 400V Mosfet	International Rectifier	IRF720S
Q2	Surface mount 55V Mosfet	International Rectifier	IRFR1205
R1, R9, R23, R14, R16	10.0k, SMT resistor, 1206 package		
R2, R28, R29	2.87k, SMT resistor, 1206 package		
R3	10Ω, SMT resistor, 1206 package		
R4	274Ω, SMT resistor, 1206 package		
R5, R6, R24	2.2k, SMT resistor, 1206 package		
R7	2.2Ω, 1W surface mount	Digikey	P2.2UCT
R8	100k, 1W axial		
R10, R12	2.2k, SMT resistor, 1206 package		
R11	750Ω, 1W axial		
R15, R18	15k, SMT resistor, 1206 package		
R17	162k, SMT resistor, 1206 package		
R19, R27	150Ω, SMT resistor, 1206 package		
R20, R22	500k, SMT resistor, 1206 package		
R13,R21	50k, SMT resistor, 1206 package		
R25	0.1Ω, 1W surface mount		
R32	150Ω, 1W axial		

Table 1. Charger Parts List (continued)

S1	Momentary push switch, SMT		
T1	CTX08, 13959-X5	Coiltronics	
U1	UCC3954 in 20 pin SOIC package	Unitrode	
U2	Diode Bridge		

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