AN11139

Off-line Li-Ion battery charger solution with the LPC111x family

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Document information

Info	Content
Keywords	LPC11xx, Cortex-M0, Li-Ion battery charger, PWM, 10-bit ADC
Abstract	A simple Li-Ion battery charger solution using the LPC111x family of Cortex-M0 of microcontrollers is presented

Revision history

Rev	Date	Description
1	20120101	Initial version.

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1. Charging principle

1.1 Introduction

Due to the rise of portable electrical systems and products using rechargeable batteries as their power supply, there are many choices for different charging methods, such as special power management ICs, MCUs, or even simple logic parts.

Low cost, high performance NXP MCUs can be used for Li-ion battery charging. Due to their high performance, they can also perform other “housekeeping” tasks concurrently.

The solution detailed in this application note is suitable for charging single cell Li-Ion batteries.

CAUTION: Li-Ion batteries should never be subjected to over-charging as this can affect the battery life as well as cause a safety hazard.

1.2 Charging phase

For most chargers, the charging procedure is divided into four main phases:

1. Pre-charge phase (depending upon the battery condition)
2. Constant-current charge phase
3. Constant-voltage charge phase
4. An optional timed constant-voltage charge phase

The pre-charge phase is used when the battery cell voltage is initially below 3.0 V. In the pre-charge phase, a low constant-current charge protects the battery in this low voltage state. However, in most recharging situations, this phase may be skipped and charging may proceed to the next phase for batteries that still have a certain voltage remaining,

The constant-current and constant-voltage phases are the main charging phases for recharging the batteries, where most of the charging energy is transferred into the battery. The maximum charging current for a battery is dependent upon the battery’s rated capacity. Li-Ion batteries are typically charged between 0.5 C and 1 C in the constant-current stage, with the value determined by the battery manufacturer. For example, a battery rated 700 mAh can usually be charged at 350 mA, but this may be as high as 700 mA, depending on the manufacturer’s specification.

In the next charging phase, the microcontroller maintains a constant charging voltage, while monitoring the charging current to determine when the charging procedure should be completed.

When the battery is fully charged, any additional charge will be converted into thermal energy. This can result in a temperature rise in the battery. In this case, the temperature monitoring function can be added to the solution. Many Li-Ion battery modules have this over-charging protection function built in, so the temperature detect function may not be required.

1.3 Buck converter

1.3.1 Buck converter operation

A buck converter is usually used in the constant-current and voltage charge phases, and is the most economical way to create a tapered termination charge. A buck converter is a switching regulator that uses an inductor as an energy storage device.

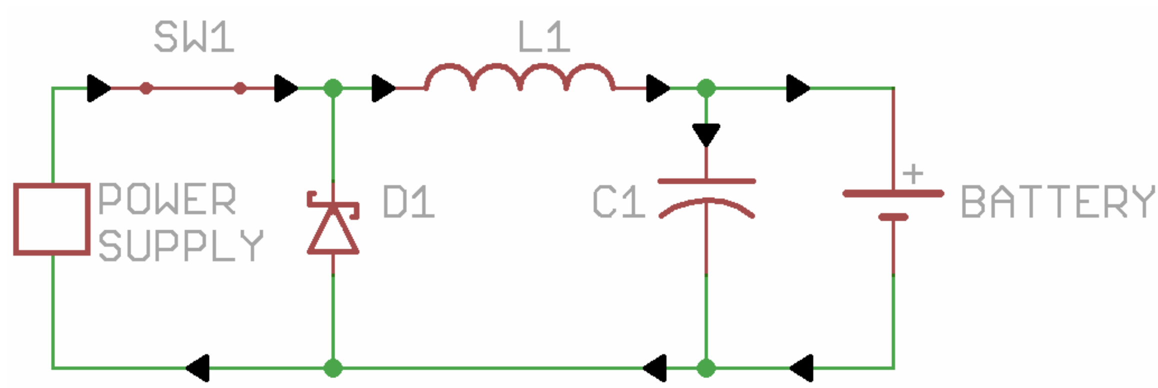


Fig 1. Buck converter with switch closed

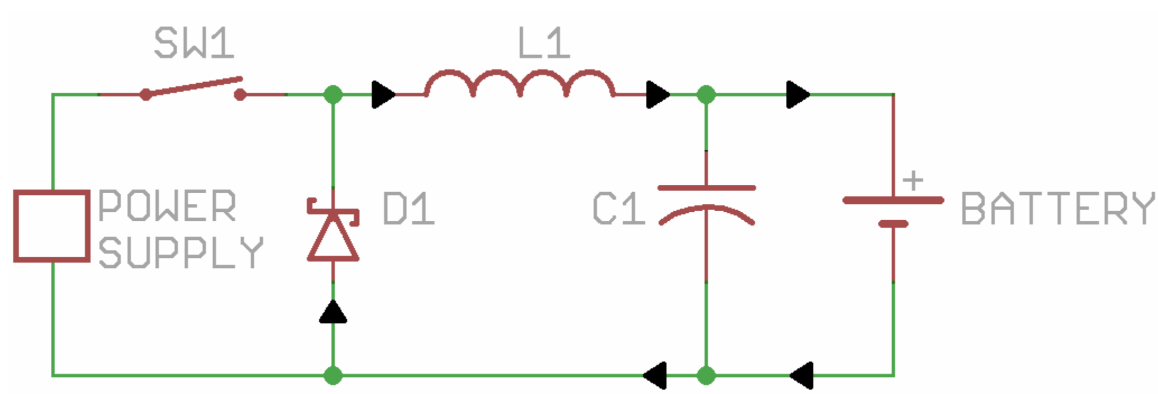


Fig 2. Buck converter with switch open

The charging switch SW1 is controlled by the microcontroller's PWM. When the switch is closed, current will flow as shown in Fig 1. The capacitor C1 is charged by the power supply through inductor L1. When the switch is open, as shown in Fig 2, the inductor will try to maintain its current flow by inducing a voltage, as the current through an inductor can't change instantaneously. The current flows through the diode and the battery, then the cycle repeats itself.

When we reduce the switch closed time (the PWM duty cycle is decreased), the average voltage decreases while an increase in the duty cycle will increase the average voltage. Therefore, controlling the duty cycle allows us to regulate the charging voltage or the charging current to achieve the desired characteristics.

1.3.2 Buck converter inductor selection

Converter inductor selection can be calculated by using the following equation:

$L = (V_i – V_{sat} - V_o) * (T * DutyCycle) / (2 * I_o)$

- V_i: charger voltage input to switch
- V_{sat}: voltage loss on switch when switch is on
- V_o: voltage output
- T: the period of the PWM
- DutyCycle: the duty cycle of the PWM
- I_o: current output (the current for constant-current charge)

As this equation shows, a higher PWM switching frequency (smaller T) allows the use of smaller inductors, which lowers the cost.

Note that the capacitor in this circuit is simply a ripple reducer, with larger values producing better ripple rejection.

2. LPC111x charger solution

This solution uses the NXP LPC111x as the controller for an off-line Li-Ion battery charger. It alternates constant-current charging and constant-voltage charging for fast charging, with LEDs as status indicators.

2.1 LPC111x features

The LPC111x is a low-cost Cortex-M0 microcontroller family with 4 kB of flash and 1 kB SRAM in the LPC1110 to 32 kB flash and 4 kB SRAM in the LPC1114. The flash memory can be programmed in-circuit.

These microcontrollers have 10-bit ADCs, four timers (two 32-bit and two 16-bit timers), as well as other peripherals, such as SPI, I²C, and a UART. The 16-bit timer is used for the PWM output of the buck converter, saving the 32-bit timers for other purposes. As the frequency of the PWM is not critical, the internal 12 MHz (±1 %) RC oscillator is used, saving the cost of a crystal.

The LQFP package was used for this project; however, the code size is small enough to fit into the 20-pin LPC1110FD20.

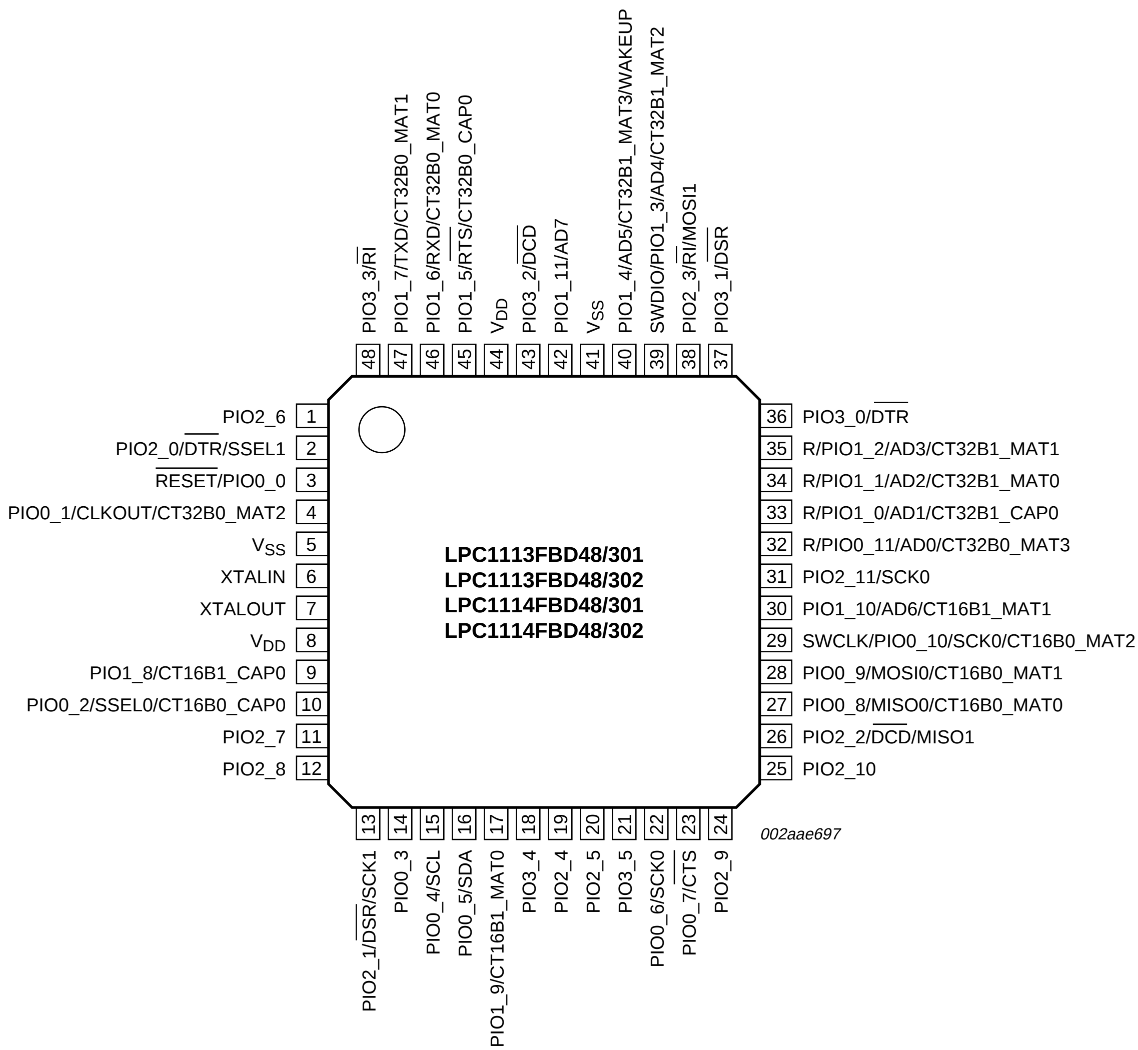


Fig 3. LPC111x pin configuration

2.2 Key design points for this solution

2.2.1 Precise power source supply for LPC111x

Because the V_{DD} voltage for LPC111x is used as the reference voltage for the A/D converter, its precision is very important. An LDO regulator is required for this. Ferrite beads were added for additional filtering of the microcontroller's supply voltage, however, this may not be needed.

2.2.2 PWM output to control charging voltage

The LPC111x provides a PWM output for the buck converter switch control. When using the on-chip RC oscillator and PLL, the clock speed of the microcontroller is 48 MHz, allowing the PWM frequency to be set to 192 kHz, and the buck converter's "on" time is then adjusted by the PWM duty cycle. The duty cycle of the PWM has a resolution of 250 steps when operating at 192 kHz. The higher PWM frequency allows the use of a smaller inductor and output capacitor.

It is also possible to create other PWM frequency and resolution combinations. For example, you could use a 96 kHz PWM with a 500 step resolution, or you could go up to 480 kHz with a 100 step resolution.

2.2.3 Apply ADC for battery charging voltage and current measurement

The LPC111x with 10-bit on-chip high speed A/D converters provides superior accuracy for monitoring charging voltage and current. It is critical to prevent overcharging in Li-Ion applications. It provides maximum effectiveness, safety, and longer battery life.

2.3 Selecting buck converter inductor

The minimum value for the inductor used for the buck converter can be calculated using the following Equation:

$L = (V_i - V_{sat} - V_{diode} - V_o) * (T * DutyCycle) / (2 * I_o)$

Assuming V_i is 5.1 V, the V_{sat} of the PNP pass transistor (at Io = 350 mA) is 0.15 V, the V_f of the Schottky diode is approximately 350 mV, the desired output voltage V_o is 4.2 V, the desired output charge current Io is 0.35 A, 1/T is 192 kHz, and the Duty Cycle is 50 %. In our circuit we also added a Schottky diode for reverse supply protection, so this should be taken into consideration if added in the user application.

The inductor should be at least 1.5 uH. In this solution, we will use a value of 10 uH for the buck converter inductor.

Note that if you would like to use a higher input voltage, you must use a higher frequency PWM, or you must use larger value inductor (at a greater cost), so a suitable input voltage is something that must be considered.

3. Specification

3.1 Input specification

- Input voltage DC 5.1 V
- Input voltage min: 5.0 V, max: 5.5 V
- Input current 500 mA
- Input current limit min: 400 mA
- Input ripple max: 50 mV (peak-to-peak)

3.2 Output specification

- Output voltage (V_o) (Constant-Voltage Charging) DC 4.2 ± 1 %
- Output voltage min: 0 V, max: 4.27 V
- Output current (constant-current charging) 350 mA ± 10 %
- Output current min: 0 mA, max: 385 mA
- Output ripple max: 50 mV (peak-to-peak)

4. Main function

4.1 Charging method

- Prepare charging with a small current (65 mA), while monitoring the battery voltage
- Fast charging with a constant current (350 mA), adjust control pulse to maintain stable current
- Fast charging with a constant voltage (4.2 V), monitor the charging current
- Top up the charge with a constant voltage (4.2 V) for a fixed period of time

4.2 Charging current

- Pre-charge current: 65 mA
- Fast charging current: 350 mA
- End charging current: < 50 mA

4.3 Four charging phases

1. Pre-charge phase, for empty batteries with voltages less than 3 V
2. Fast constant-current phase
3. Constant-voltage charge
4. Optional timer controlled constant-voltage charging phase, lasting 50 minutes

4.4 Termination criteria

- Error detection: battery voltage < 1 V, or over 4.6 V (open circuit)
- Time control
- Battery temperature test (optional) and not implemented

4.5 LED indicators

- Green LED blinking:
  - 4 seconds for pre-charge
  - 2 seconds for constant-current charge
  - 1 second for constant-voltage charge
  - 0.5 seconds for 50 minute timed charge
- Green LED on: Charging completed successfully
- Red LED on: Battery not in circuit or battery voltage less than 1 volt

4.6 Output short protection

If output is shorted, the controller will automatically identify this state by detecting a low voltage. It will shut down the PWM and turn the red LED on.

4.7 Battery out of socket indicator

When charging starts, if the battery is not in the charge socket, then the charger will indicate this by turning the red LED on. When charging, if the battery is removed from the charger socket, the charger will indicate this by turning the red LED on. To continue charging, the charger needs to be reset.

5. Charging Time

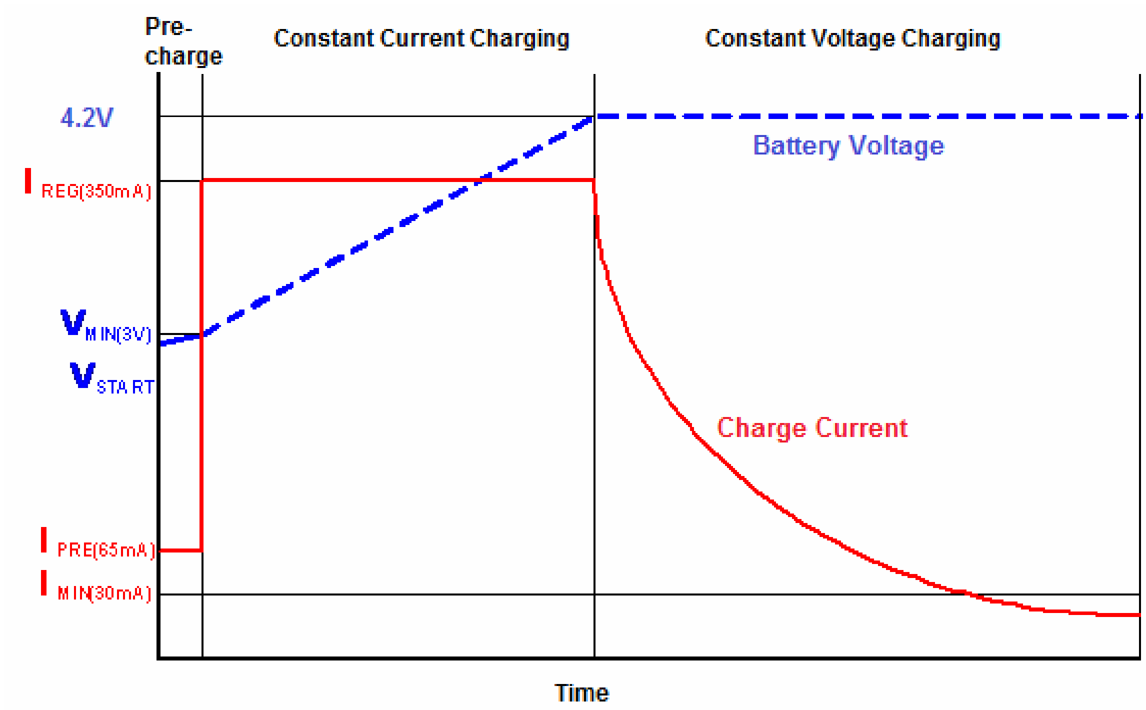


Fig 4. Charging phases

5.1 Four charging phases:

- Pre-charge phase (when needed)
  – If Vbat < 3.0, set Iout = 65 mA
- Fast charging phase (Constant-current charging)
  – Vbat < 4.2 V, set Iout = 350 mA
- Fast charging phase (Constant-voltage charging)
  – Vout = 4.2 V, Ibat ≧ 50 mA
- Optional timer controlled charging phase (constant-voltage charging)
  – When Ibat **<** 50 mA, set Vout to 4.20 V for 50 minutes to ensure that battery is fully charged, then end the charging procedure.

The entire charging process is expected to end within 5 hours, but the actual time will vary depending upon the initial charge in the battery, as well as the battery capacity.

6. Implementing the battery charger

The schematic for the battery charger can be found in Appendix B. The positive side of the battery is connected to terminal J1, while the negative side is connected to terminal J2.

Different current values can be implemented by the user, depending upon the battery's charging limitations and capacity. The values defined for the constant-current section can be modified by changing the following define:

```
#define MA350 81
```

This value is determined by the voltage generated across the 0.75 ohm current sense resistor R2, when charging at 350 mA, and converted into a value that the 10-bit ADC would read, assuming a 3.3 V voltage reference ((0.35A * 0.75 ohm) / 3.3V * 1023 = 81).

The constant-voltage phase is ended when the current reaches 50 mA. This value is determined using the same method as used for the constant current definition:

```
#define MA50 12
```

The timer for final phase is set at 50 minutes, but may be changed by the user. The SYSTICK timer generates an interrupt every 1 ms, where a counter is incremented. For a 50 minute timing interval, this value is set to (50 minutes * 60 seconds * 1000 = 3,000,000):

```
#define MIN50 3000000 /* 50 minutes in "TimeTick" counts     */
```

7. Conclusion

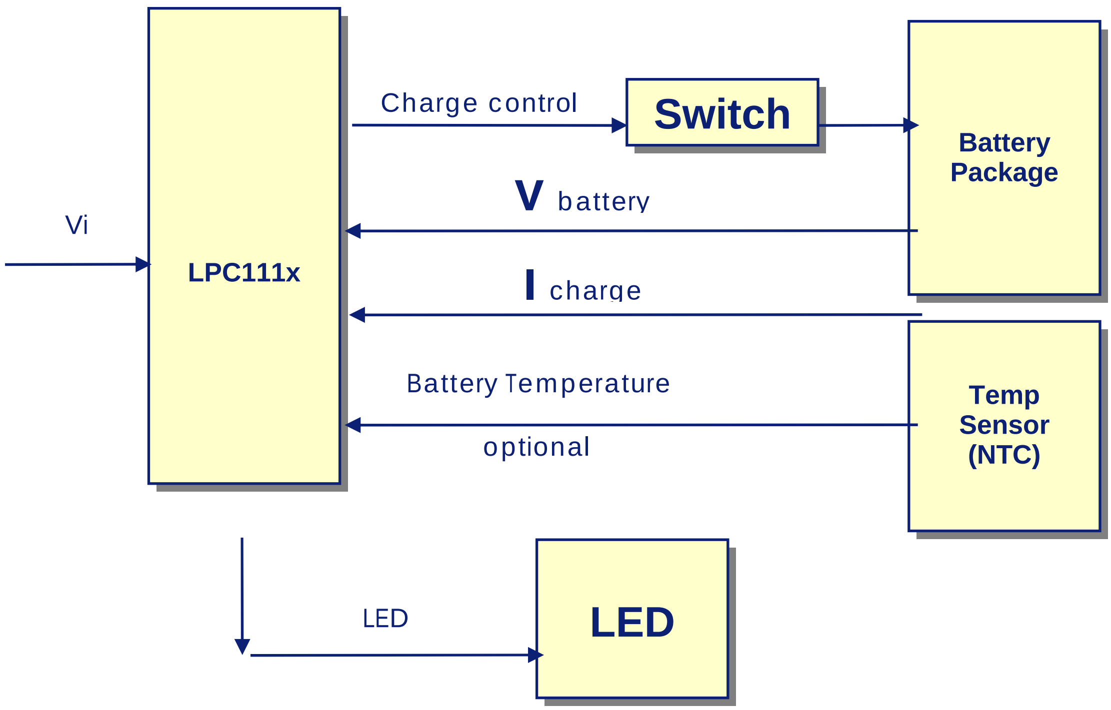
This example project describes how to implement a single cell Li-Ion battery charger using an LPC111x Cortex-M0 microcontroller, using minimal external components.

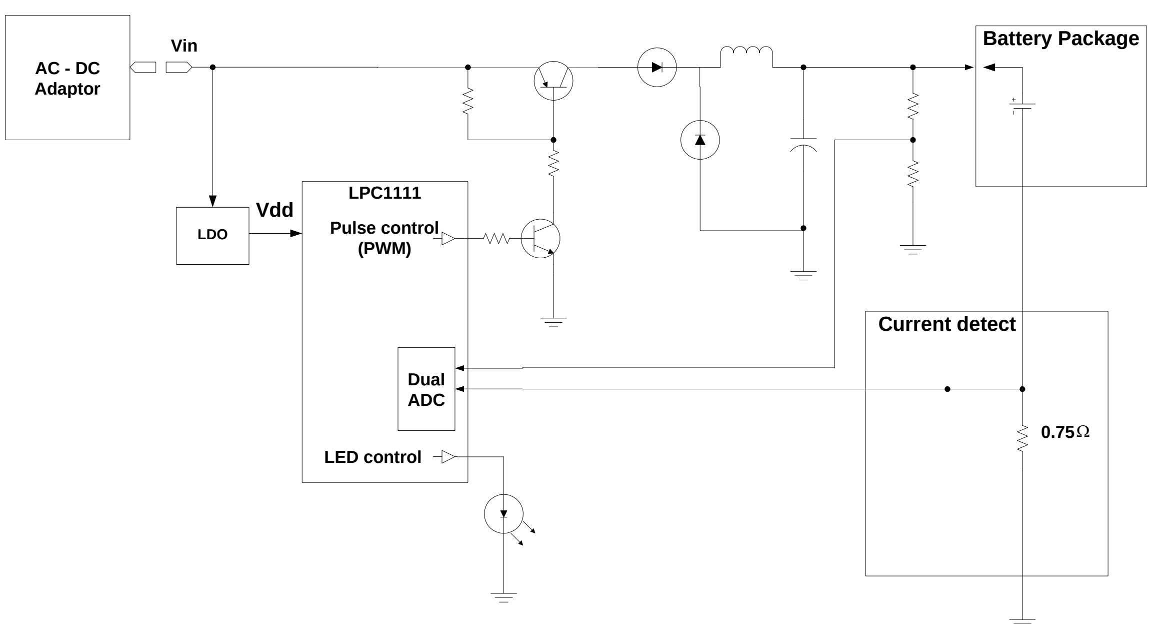
The charger requires very few of the microcontroller's resources (one PWM using a 16-bit timer, two or three channels of ADC, and the Systick timer), leaving sufficient bandwidth and peripherals for the addition of other functions and features to be added to the project.

Li-Ion batteries are typically charged between 0.5 C and 1 C in the constant-current stage, with the value determined by the battery manufacturer.

Li-Ion batteries should never be subjected to over-charging as this can affect the battery life as well as causing a safety hazard.

8. Appendix A: Functional block diagram





9. Appendix B: Schematic

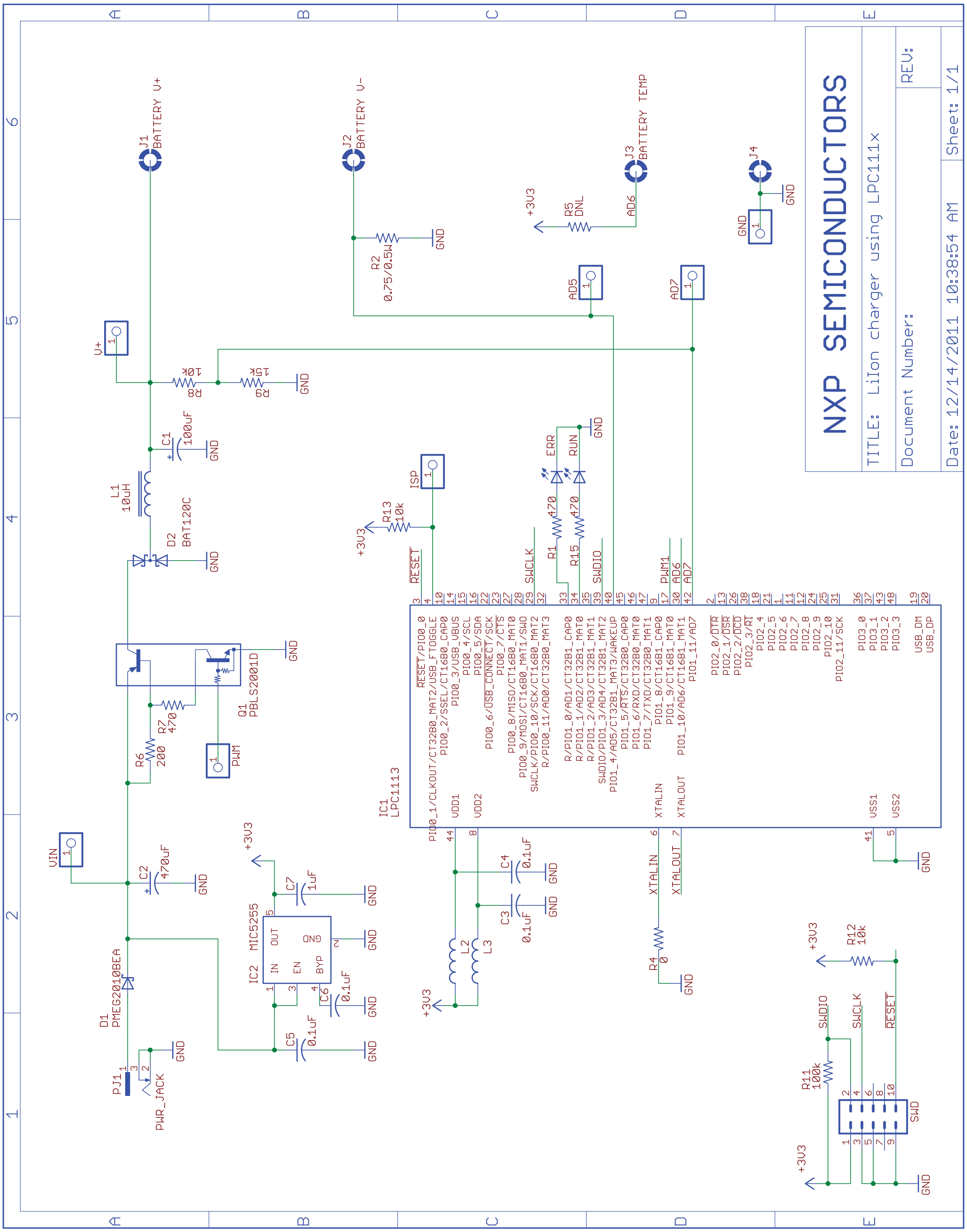


Fig 5. Lithium Ion charger schematic

10. Appendix C: Component selection

The values of C1 and C2 have an impact on the input and output ripple voltages. When there is no input capacitor C2, there is significant ripple voltage seen at Vin (Fig 6). The power supply is a typical AC-DC converter rated at 5V/2A and the charger is operating in the 350 mA constant-current mode.

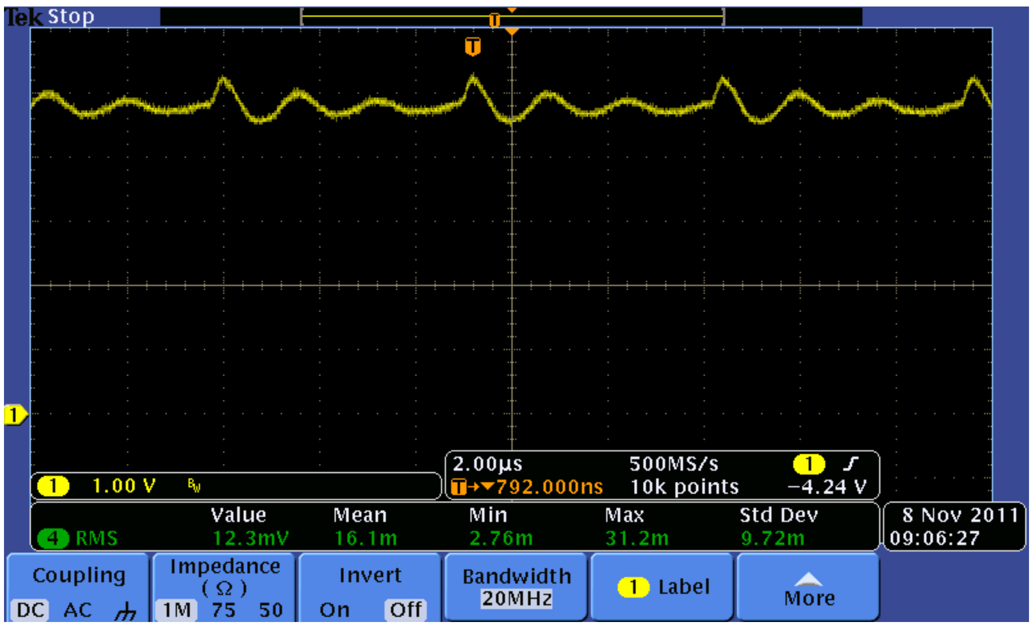


Fig 6. Input ripple voltage without input capacitor C2

Adding a 470 uF capacitor significantly improves the input ripple voltage as seen at Vin.

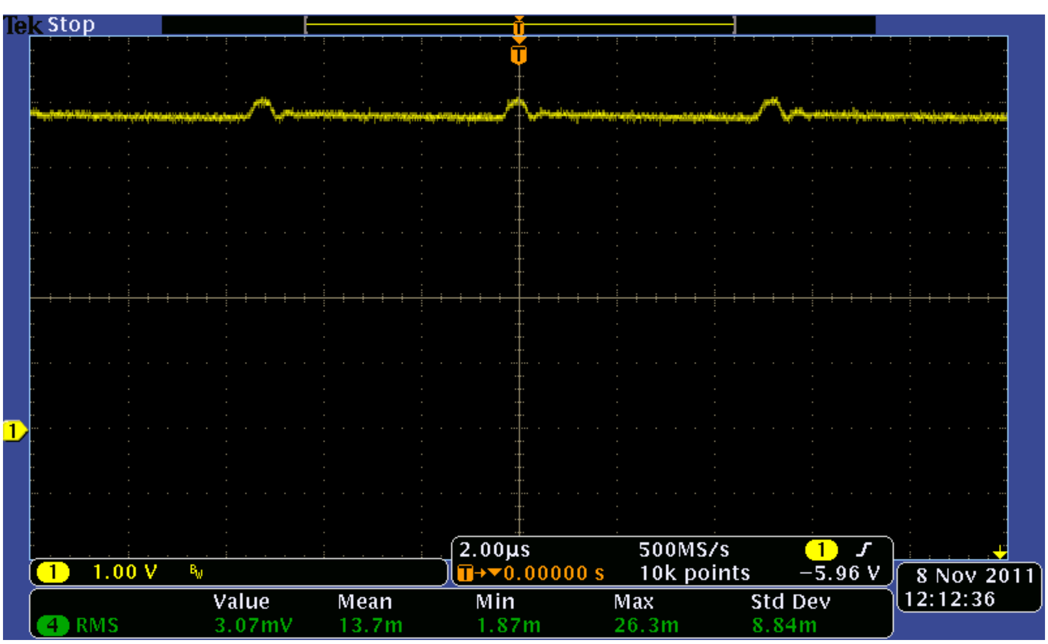


Fig 7. Input ripple voltage with 470 uF capacitor

The output capacitor selection will affect the output ripple voltage. Our design criterion was 50 mV peak-to-peak. When a 22 uF tantalum capacitor was selected for C1, a ripple voltage of 54 mV was seen.

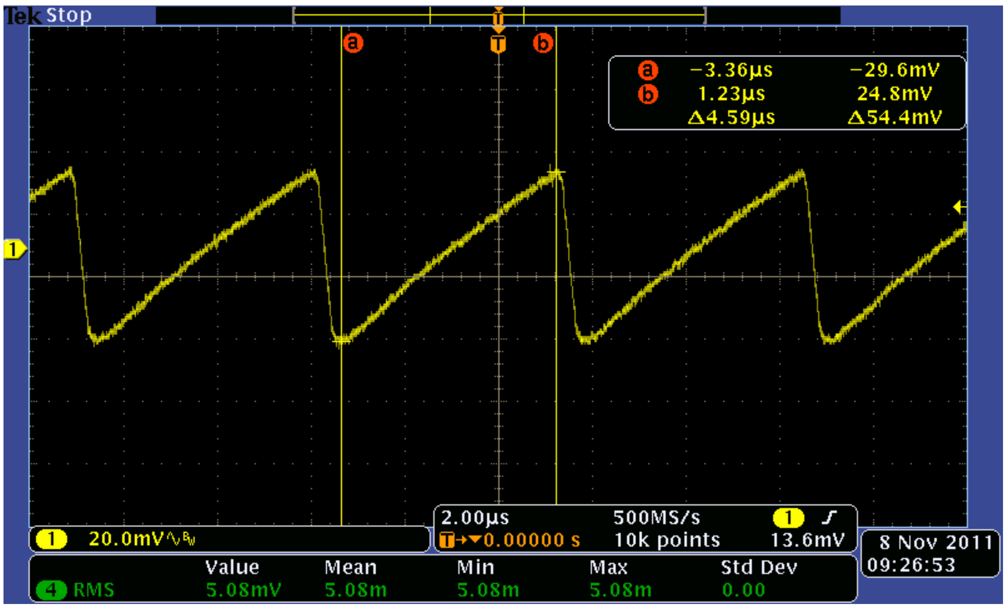


Fig 8. Output ripple voltage with 22 uF C1

Increasing output capacitor C1 to 100 uF improved the ripple to less than 20 mV as seen in Fig 9.

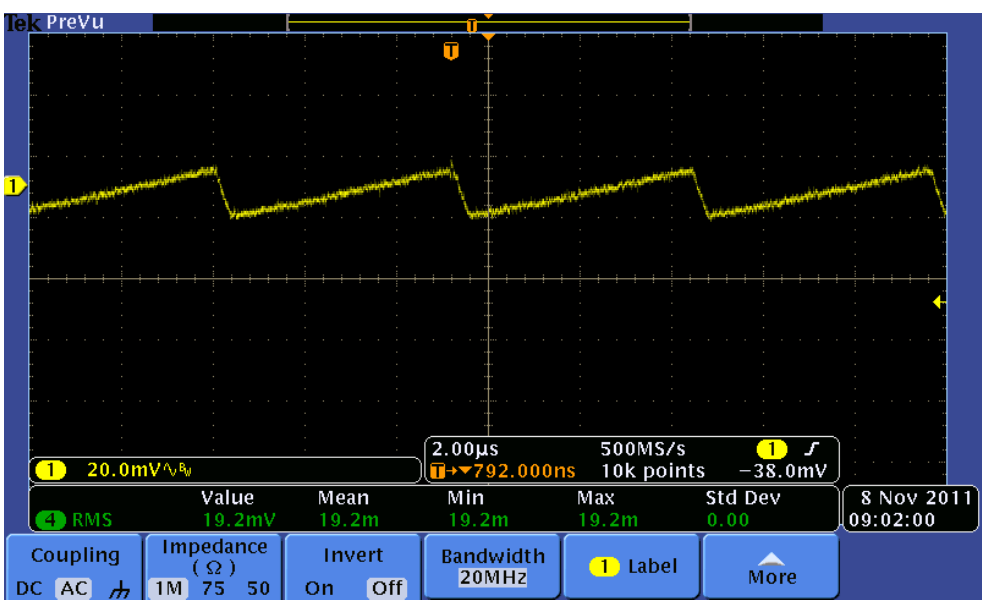


Fig 9. Output ripple voltage with 100 uF C1

A value of 33 uF would be sufficient to meet the 50 mV requirement; however, we used 100 uF for our testing.

11. Software flowchart

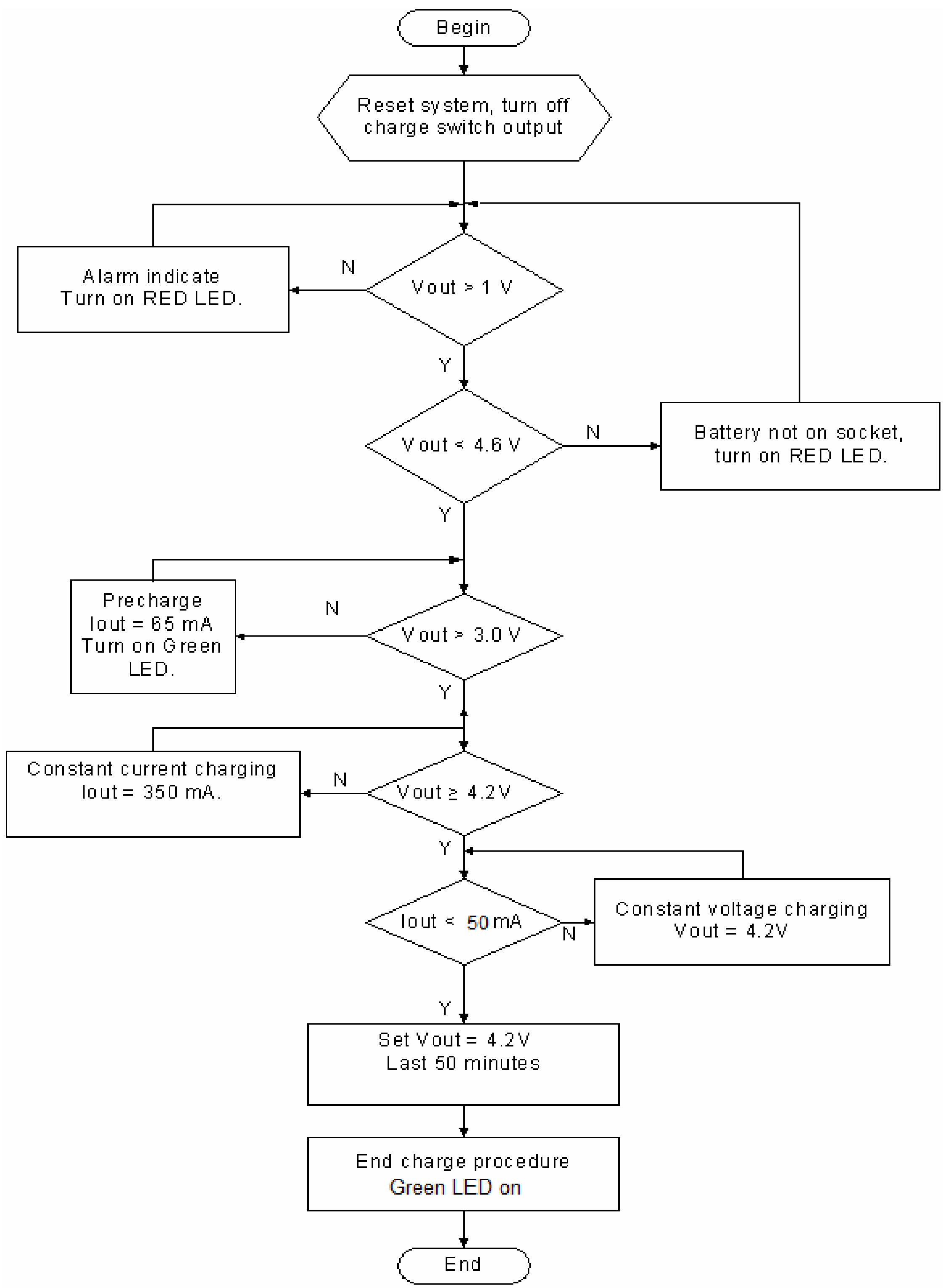


Fig 10. Software flowchart

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