AN1156

Battery Fuel Measurement Using Delta-Sigma ADC Devices

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INTRODUCTION

The battery fuel status indicator is a common feature of the battery-supported handheld devices. The battery fuel measurement is achieved by measuring the discharging and charging currents in real time. The discharging current is the current coming out from the battery and the charging current is the current flowing into the battery. The fuel used (mAH) and the fuel remaining (mAH) are calculated by tracking the discharging and charging currents over time. The fuel used is the total discharged current over time and the remaining fuel is simply the subtraction of the fuel used from the fully charged fuel.

The behavior of the battery fuel is greatly affected by temperature and the battery aging. A true battery management needs to consider these effects by measuring current, voltage, and temperatures with a function of time.

The battery voltage and current measurement is achieved using an analog-to-digital converter (ADC). The accuracy of the fuel management relies on the accuracy of the ADC performance. Measuring the battery voltage is straightforward. However, the current measurement is achieved indirectly using a current sensor. The current sensor has a resistive component. When the current flows through the current sensor, there is a voltage drop across the sensor element. The current is calculated by measuring the voltage drop on the known resistive value of the sensor. The system designers must be aware that the voltage drop across the current sensor is waste that brings down the battery voltage budget for the system. Therefore, it is best to use a current sensor that has the smallest resistance value, as possible.

The voltage drop across the current sensor is inversely proportional to the resistance value of the sensor element. If the ADC bit resolution is not enough, the system may not be able to detect the current in µA or low mA range, unless the current sensor has a high resistance value. Therefore, for current measurement, a high bit resolution ADC or a high resolution ADC with internal programmable gain amplifier (PGA) is preferred.

Today's integrated battery fuel gauging devices include both the ADC and the control logic circuits. The feature sets for these devices are still evolving to meet general application specifications. These devices are still relatively expensive for cost-sensitive product designers. Furthermore, due to the limitations in bit resolution of the internal ADC circuit, the accuracy may not be sufficient for certain applications.

Instead of using the integrated fuel gauging devices, some clever designers create their own fuel gauging algorithm by using firmware for the microcontroller unit (MCU). The current and voltage are measured using a stand-alone ADC device of their choice. This choice provides flexible solutions for their application and enables them to manage their battery fuel economically. Since the MCU is used regardless of which option is chosen, the cost-saving can be significant in high volume applications. Depending on the battery used and the application, the system designers can make various tradeoffs in the fuel measurement. Some designers only need battery voltage for simple applications or some need a sophisticated fuel gauging function for accurate applications.

This application note reviews the battery fuel measurement using the MCU and ADC devices.

REVIEW OF BATTERY CHARGING AND DISCHARGING CHARACTERISTICS

The battery discharging behavior changes with various parameters, such as battery chemical type, load current, temperature, and aging. Figure 1 shows the battery discharging curves of several battery chemical types. The battery discharging curve of most batteries is almost flat until it reaches about 80% of its full range, and then falls off sharply after that.

Since the battery's internal chemical reaction is largely governed by voltage and temperature, the battery discharging behavior is greatly affected by the temperature. The low temperature limit is determined by the freezing temperature of the electrolyte. Most batteries do not work well below -40°C. The battery performs better at higher temperatures. This is because the chemical reaction processing is accelerated at higher temperatures. However, the rate of undesirable chemical reactions increases and results in an acceleration of battery life. At extremely high temperatures, the active chemicals become unstable and can destroy the battery.

Figure 2 shows the battery discharging curve versus temperature. As shown in Figures 1 and 2, a true battery fuel management system requires monitoring both the current, the voltage, and the temperature.

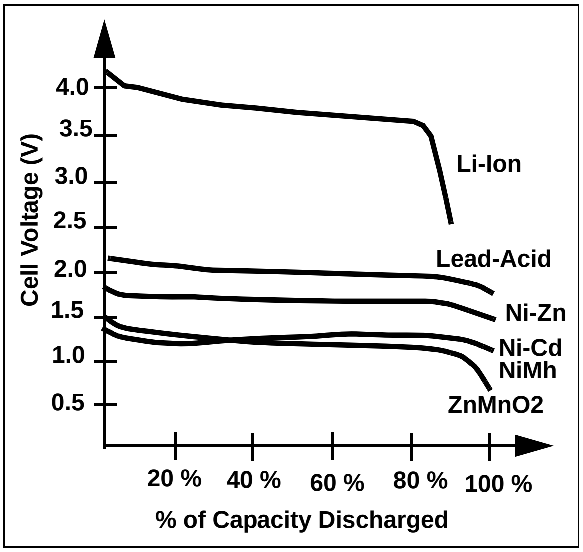

FIGURE 1: Battery Discharge Characteristics.

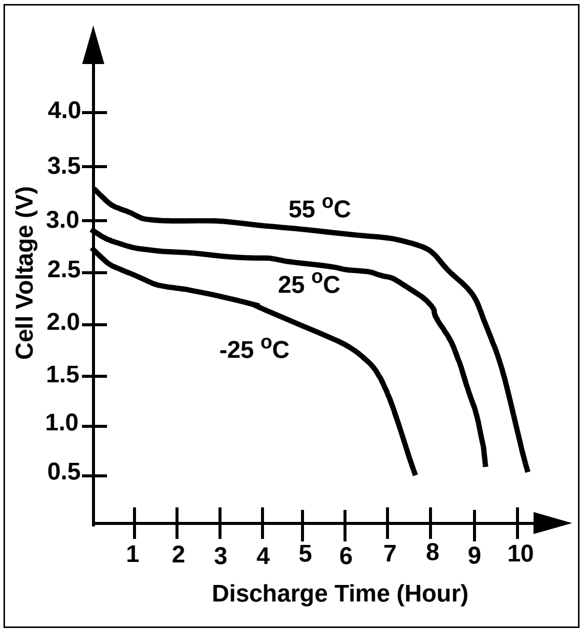

FIGURE 2: LI-Ion Battery Discharge Characteristics vs. Temperature.

KEY FEATURES OF THE MCP3421 18-BIT DELTA-SIGMA ADC FAMILY

The MCP3421 ADC family has unique features for voltage and current measurement applications. The MCP3421 is an 18 bit, single channel, Delta-Sigma ADC with user programmable configuration bit settings. The device has two operating modes: (a) Continuous and (b) One-Shot mode. In the continuous mode, the device performs conversions continuously. During the conversion time, the device draws about 140 µA. However, in the One-Shot mode, the device automatically switches to current saving mode after one conversion is completed. Assuming the device is configured for 18 bit mode, and taking data once per second, it draws only about 40 µA. In standby mode, it draws only about 100 nA. This feature is extremely useful for battery powered low power applications.

The device has an internal programmable gain amplifier (PGA) with a gain of up to 8 and an internal reference voltage of 2.048V. This PGA gain feature is very useful when measuring low voltage drops across the low resistance current sensor. The input is internally multiplied by a factor of 8 before the ADC conversion takes place. This means the PGA can detect an input signal eight times lower than its LSB size. The 2.048V internal reference voltage is useful because the ADC performance is not affected by the V_{DD} variations. However, it limits the input range to a maximum of 2.048V. Because of this limit, a simple voltage divider circuit may be necessary to measure a battery voltage higher than the reference voltage. The MCP3421 family consists of single, dual, and four channels devices.

Key features of the MCP3421 device family are:

- Programmable ADC resolution:
  - 12 bits, 14 bits, 16 bits, or 18 bits.
- Differential or single-ended input operation
- On-board Voltage Reference
- On-board Programmable Gain Amplifier (PGA):
  - Gains of 1, 2, 4 or 8
- One-Shot or Continuous Conversion Options
- Low current consumption:
  - 145 µA typical in Continuous Conversion)
  - One-Shot Conversion (1 SPS) with V_{DD}= 3V:

    39 µA typical with 18 bit mode

    9.7 µA typical with 16 bit mode

    2.4 µA typical with 14 bit mode

    0.6 µA typical with 12 bit mode

BATTERY VOLTAGE MEASUREMENT USING ADC

Figure 3 shows the battery voltage measurement circuit using the MCP3421 device (U1). Since the MCP3421 device has an internal reference voltage, the measurable maximum input voltage range is limited to the internal voltage reference voltage of up to 2.048V. Therefore, to measure the input voltage higher than the internal reference, a voltage divider is needed formed by R_1, R_2, and R_3. The R_3 is optional and is used to calibrate the R_1 and R_2 component tolerance. By choosing the series resistance value of the voltage divider to be very high (> 1 MΩ), the current losses due to the voltage divider is negligible.

In the example circuit as shown in Figure 3, the ADC is configured as single ended by connecting the positive input pin (V_{IN}+) to the battery voltage, while the negative input pin (V_{IN}-) to the V_{SS}. The ADC output is available to the MCU via the I^2C bus line.

Figure 4 shows the discharge curve of a 3.7V Li-Polymer battery (3.7V, 170 mAH). The curve shows that the battery voltage reduces linearly until it reaches about 80% of its full capacity.

Since the battery discharging characteristics are very linear until the point where the curve falls off sharply, measuring only the battery voltage is an alternative low-cost method to estimate the current status of the battery. In this case, the measured battery voltage can be compared with the fuel values in the lookup table in the MCU firmware.

The circuit shown can be used for measuring the battery voltage of any battery type. When the circuit is used, the voltage divider (R_1, R_2, R_3) must be properly adjusted in order to keep the maximum input voltage (or the voltage at V_{IN}+ pin when the battery is fully charged) to the ADC device is less than the ADC internal reference voltage (2.048V).

Although using the voltage alone is not sufficient to represent the battery fuel status, this method is widely used for simple and cost-sensitive applications because of its straightforward implementation.

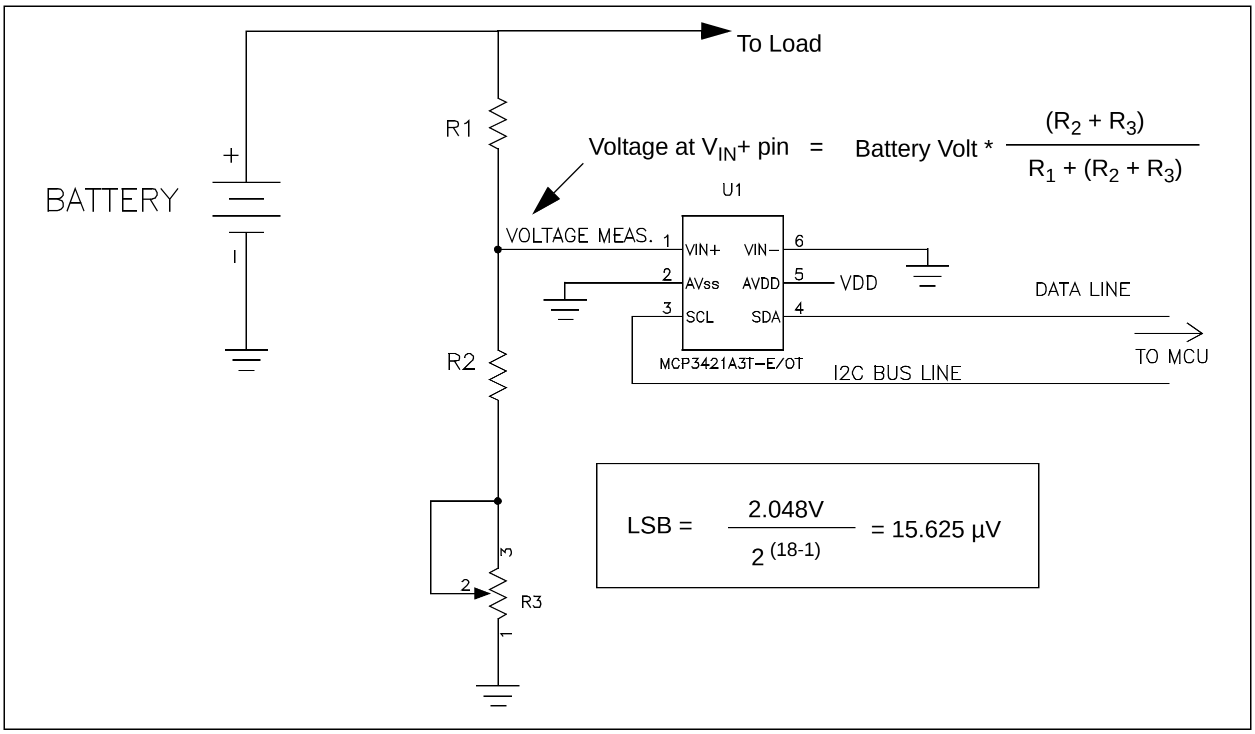

FIGURE 3: *Battery Voltage Measurement.*

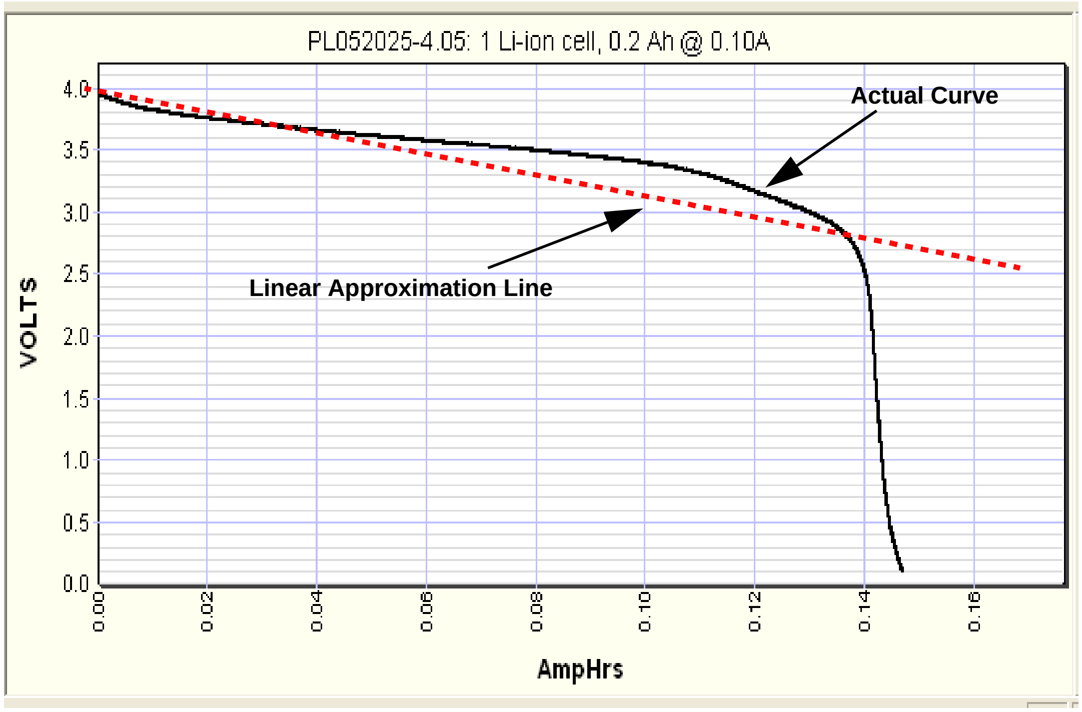

FIGURE 4: *Battery Voltage Discharging Curve of 3.7V Li-Polymer Battery.*

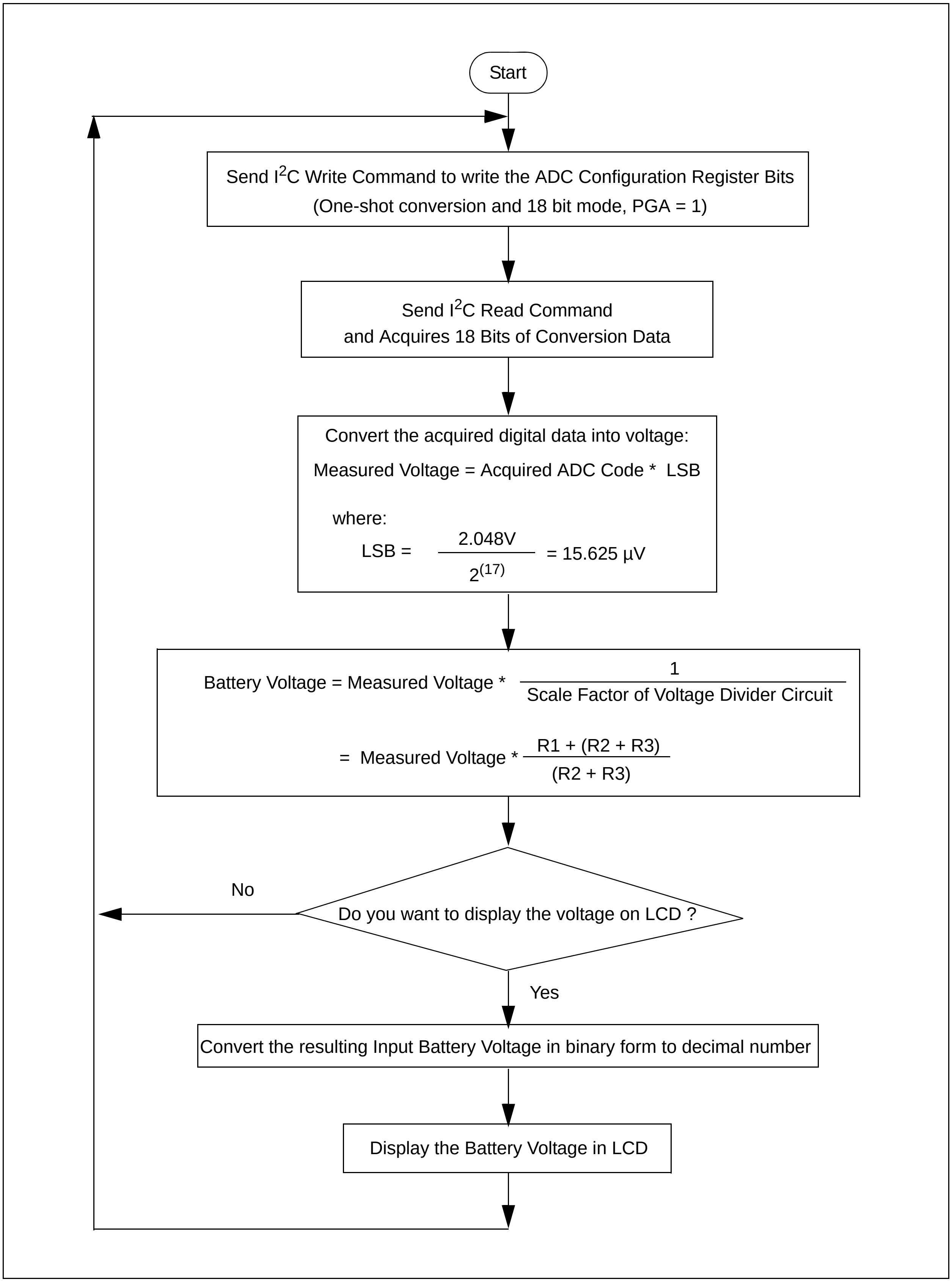

FIGURE 5: *MCU Firmware Flow Chart for Battery Voltage Measurement.*

DISCHARGING AND CHARGING CURRENT MEASUREMENT

Figure 6 shows the battery discharging and charging current measurement circuit using the MCP3421 ADC device. In the discharging mode, the direction of the current is from the battery to the load via the current sensor element. The current flows through the current sensor causing a voltage drop across the sensor due to the sensor's resistive component. This voltage drop is measured by the MCP3421 device.

In the example circuit, the MCP3421's differential input pins are connected across the current sensor. In the discharging mode, the voltage at the V_{IN}+ input pin is positive with respect to the voltage at the V_{IN}- pin. In the charging mode, the polarity is opposite due to the opposite direction of the current flow. The MCU can determine the direction of the current by testing the sign bit (MSB) in the ADC output code.

When the designers choose the current sensor, they need to consider both the battery voltage budget and the ADC bit resolution. Since the voltage drop due to the current sensor is losses, it needs to be minimized. On the other hand, it must be high enough to be measured by the ADC. In theory, the ADC can measure the input signal as long as it is greater than 1 LSB (Least Significant Bit).

EQUATION 1: LSB OF MCP3421

$$LSB = \frac{\text{Reference Voltage}}{2^{n-1}} = \frac{2.048V}{2^{17}} = 15.625\mu V$$

Where:

n = number of bit resolution

Assuming a load curret of 10 mA is passing through a 10 mΩ – current sensor, the voltage drop across the current sensor becomes 100 µV. This is equivalent to 6.4 LSB of the 18 bit MCP3421 ADC device, or 6.4 output codes. The MCP3421 device has an internal PGA. By setting the PGA to a gain of 8, the input is boosted to 800 µV internally before the ADC conversion takes place. This results in 51 LSB or 51 output codes which are sufficient for measurement.

This example shows that the current measurement needs a high resolution ADC for accurate measurement. Furthermore, the ADC with an internal PGA is the preferred choice unless you are using a relatively high resistance current sensor.

The current is calculated by dividing the measured voltage by the known resistance value of the current sensor. By doing this, the current can be measured periodically with a small time interval. The measured value is then added over time. The total fuel used is the sum of the measured discharging current over time, and the remaining battery fuel is the difference between the battery fuel when it is fully charged and the fuel used. The calculation of these parameters can be done using the MCU firmware.

EQUATION 2: CURRENT CALCULATION

$$I = \frac{\text{Measured Voltage}}{\text{R of Current Sensor}}$$

EQUATION 3: TOTAL BATTERY FUEL USED (DISCHARGED)

$$Fuel\ Used(mAH) = \sum_{n=1}^{N} Discharging\ Current(mA) \times \Delta Time(n)$$

$$Fuel\ Used(mAH) = \sum_{n=1}^{N} Discharging\ Current(mA) \times \frac{\Delta Second(n)}{3600}$$

EQUATION 4: REMAINING BATTERY FUEL

$$Fuel\ Remaining\ (mAH) = Battery\ Full\ Capacity(mAH) - Fuel\ Used\ (mAH)$$

The MCU firmware involves controlling the MCP3421 ADC device for conversion data, multiplication, division, and binary to decimal conversion. The MCU code examples for these operations are included in the attached firmware.

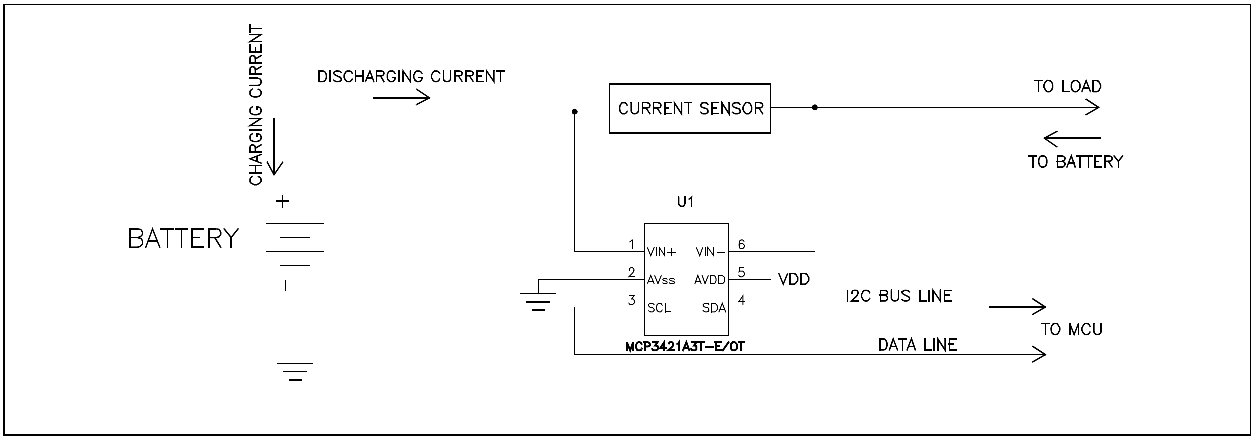

FIGURE 6: *Battery Discharging and Charging Current Measurement.*

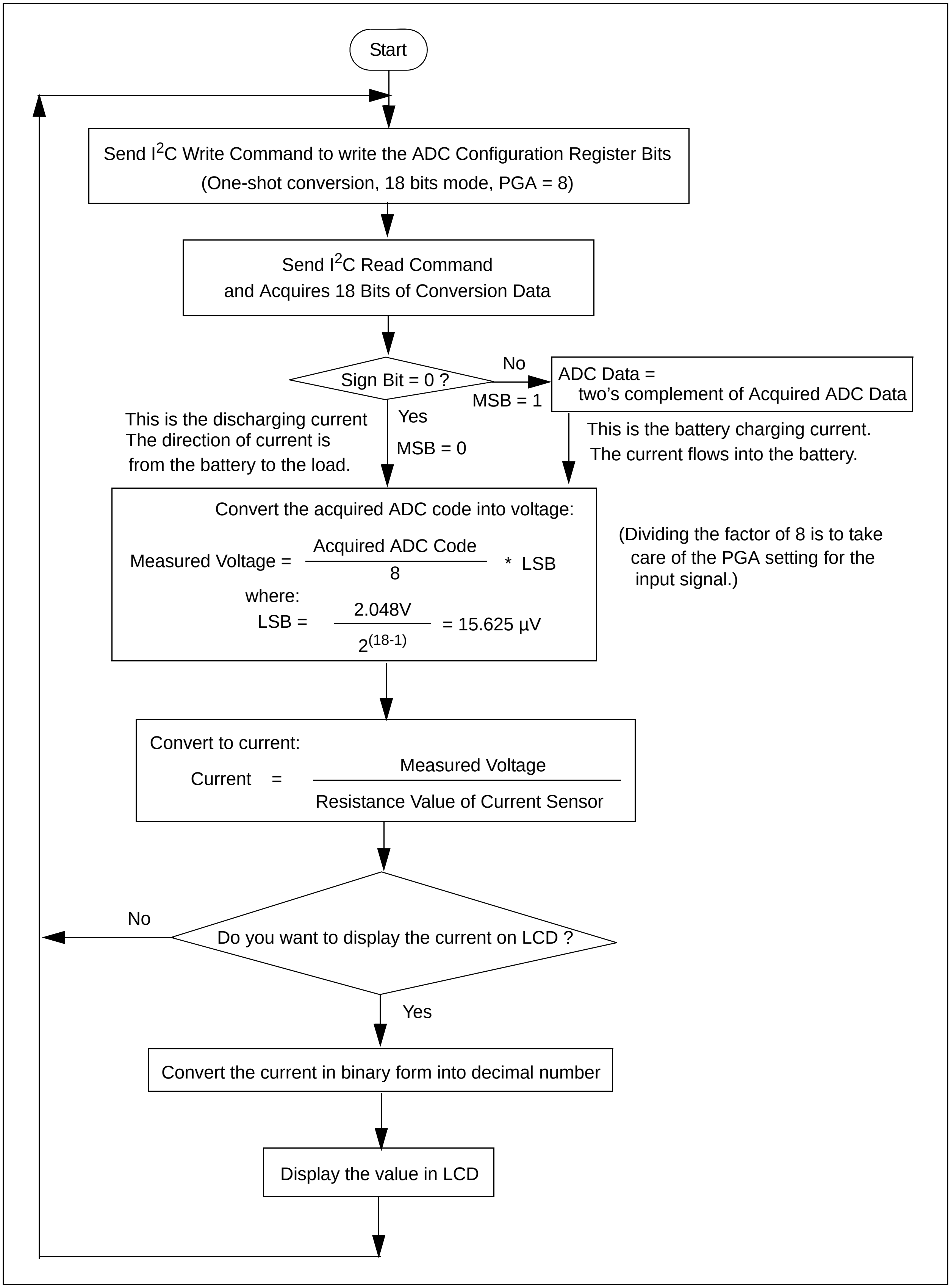

FIGURE 7: *MCU Firmware Flow Chart for Battery Current Measurement.*

VOLTAGE AND CURRENT MEASUREMENT USING DUAL CHANNEL ADC

Figure 8 shows the circuit example measuring both battery voltage and current. A dual channel MCP3421 ADC device is used for this measurement. The MCU can measure the voltage and current by multiplexing its channel. The same principles that are described in the previous sections for voltage and current measurement are applicable here, except the channel multiplexing.

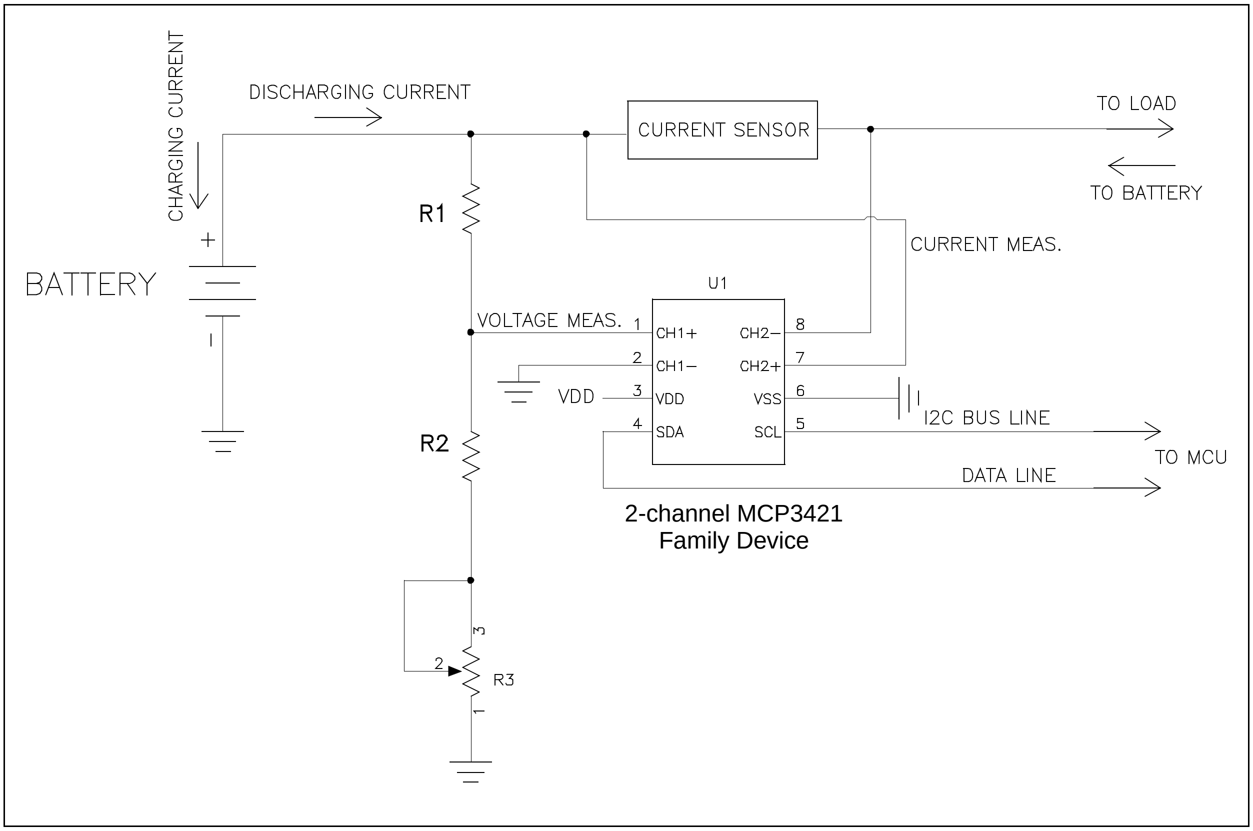

FIGURE 8: *Battery Voltage and Current Measurement.*

BATTERY FUEL GAUGING ALGORITHM USING THE MCP3421 BATTERY FUEL GAUGE DEMO BOARD

Figure 9 shows the MCP3421 Battery Fuel Gauge Demo Board and Figure 10 shows the schematics.

The MCP3421 Battery Fuel Gauge Demo Board measures the battery voltage and current every second and calculates the battery fuel being used and remaining. The measured and calculated results are displayed on LCD.

If the rechargeable battery is used, it can recharge the battery if needed. In the circuit, two MCP3421 devices are used to measure the voltage (U5) and current (U1) separately. A dual channel device (U6) can replace the U5 and U1 functions. The U6 is not populated on the board. The R3, R4, and R1 form a voltage divider circuit. The R1 is an adjustable resistor to calibrate the R3 and R4 tolerance. When the total resistance of these resistors are larger than 1 MΩ, the current draw due to the voltage divider is negligible.

R12 is the 0.01Ω - current sensor. All load currents are passing through R12.

R11 represents the total load resistance (100Ω). This value is simply chosen to represent a load condition and can be any number.

With the conditions above and a 1.5V AAA battery, the load current becomes 15 mA. The voltage drop across the current sensor is:

$$V = 15mA \bullet 0.01\Omega = 150\mu V$$

When the ADC U1 is configured with a PGA gain setting of 8 and operated with 18 bit resolution, the total number of useful digital conversion code (or counts) from the ADC device is:

EQUATION 5:

Input Voltage to the ADC Converter with PGA setting of 8 = 150 µV * 8 = 1.2 mV

$$\text{Total Number of Useful ADC Code Count} = \frac{1.2\text{ mV}}{\text{LSB (= 15.6 µV)}}$$

= 77 counts

The example in Equation 5 is measuring the current flow of 15 mA through the 10 mΩ current sensor. It shows that about 77 digital codes are useful out of the total of 131072 available codes from the 18-bit MCP3421 ADC device. These available output codes are still sufficient enough to keep track of the current of 15 mA on 10 mΩ sensor. The higher number of useful codes gives the better accuracy, and it increases with the ADC's bit resolution and PGA settings. In general, the ADC component price increases with the bit resolution due to the cost that is associated with the device test time.

By setting the PGA to a gain of 8, the MCP3421 device can measure the input voltage as low as 1.953 µV. This is the LSB size of a 21-bit ADC, which is the equivalent of gaining 3 extra bits while using the 18-bit ADC device.

The MCU firmware tracks the current flow across the current sensor and calculates the fuel used and remaining.

The MCP73831 (U3) is a single cell Li-Ion/Li-Polymer battery charger. The MCU controls the PROG pin to start or stop recharging the battery. The MCU also monitors the STATUS pin for the battery recharging condition.

Figure 11 shows the flowchart of the algorithm example used in the MCP3421 Battery Fuel Gauge Demo Kit. Since the algorithm is based on the MCU firmware, the user can easily modify the algorithms for their own.

MCU FIRMWARE EXAMPLES

The MCU firmware examples for the Figures 9, 10, and 11 are attached in this application note. The firmware is written using the PIC18F4550 MCU. The rechargeable battery is 3.7V / 170 mA Li-Ion/Polymer Battery from Powerizer (P/N: PL052025) in California (Website: http://www.batteryspace.com).

In the MCP3421 Battery Fuel Gauge Demo Board Kit, the battery recharge function is disabled, since the board is shipped to the customer with the 1.5 AAA non-rechargeable battery. However, the firmware examples in this application note use the rechargeable battery (P/N: PL052025).

The user can simulate the recharging battery feature using the MCP3421 Battery Fuel Gauge Demo Board Kit, attached firmware, and the specified rechargeable battery (P/N: PL052025). The MCP3421 Battery Fuel Gauge Demo Board Kit with this firmware tracks the battery fuel and allows the battery to be recharged after the fuel is consumed.

The MCU firmware is downloadable (File Name: MCP3421 App Note on Battery Fuel Gauge.Zip).

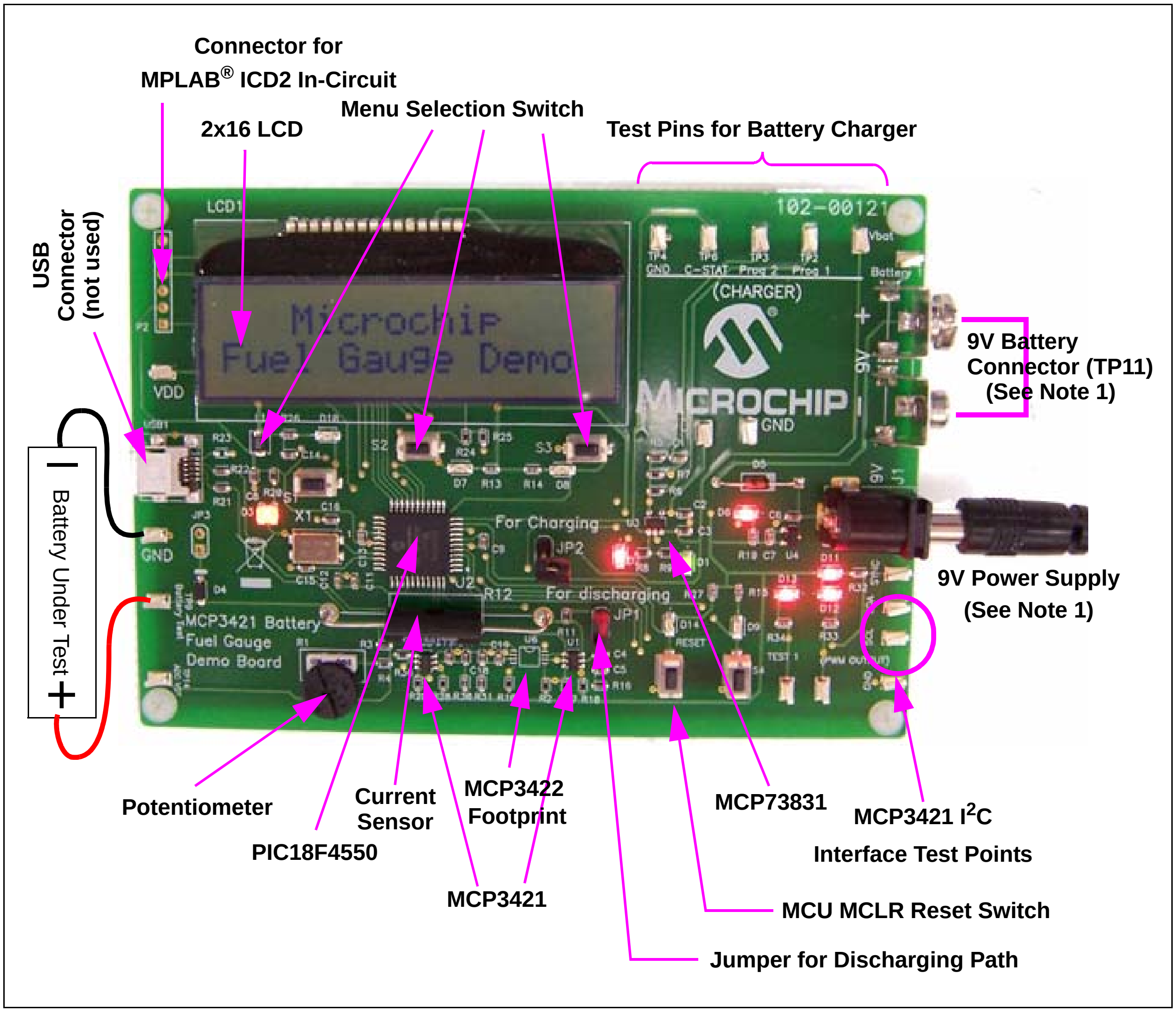

FIGURE 9: *MCP3421 Fuel Gauge Demo Board.*

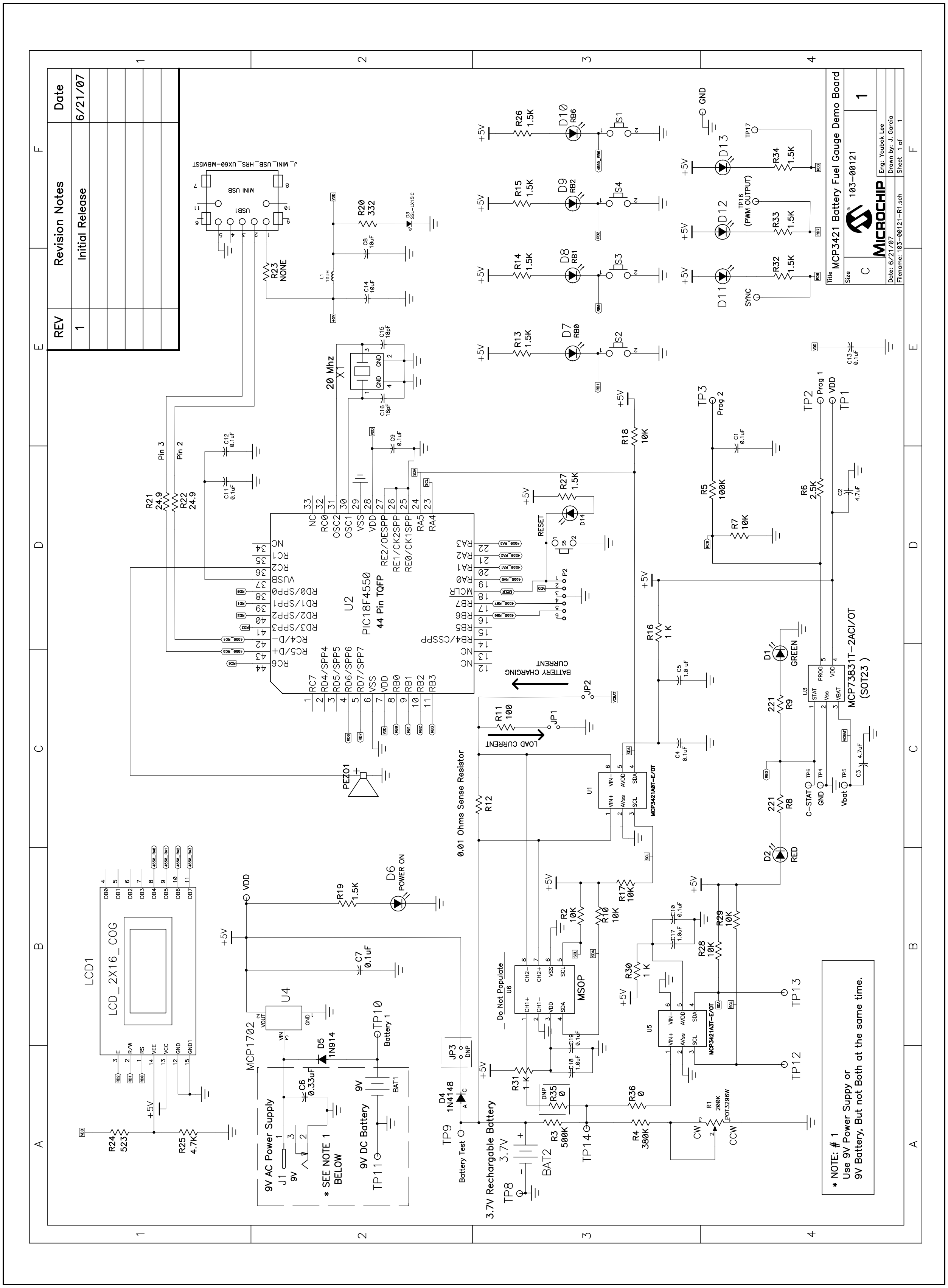

FIGURE 10: *MCP3421 Fuel Gauge Demo Board Schematic.*

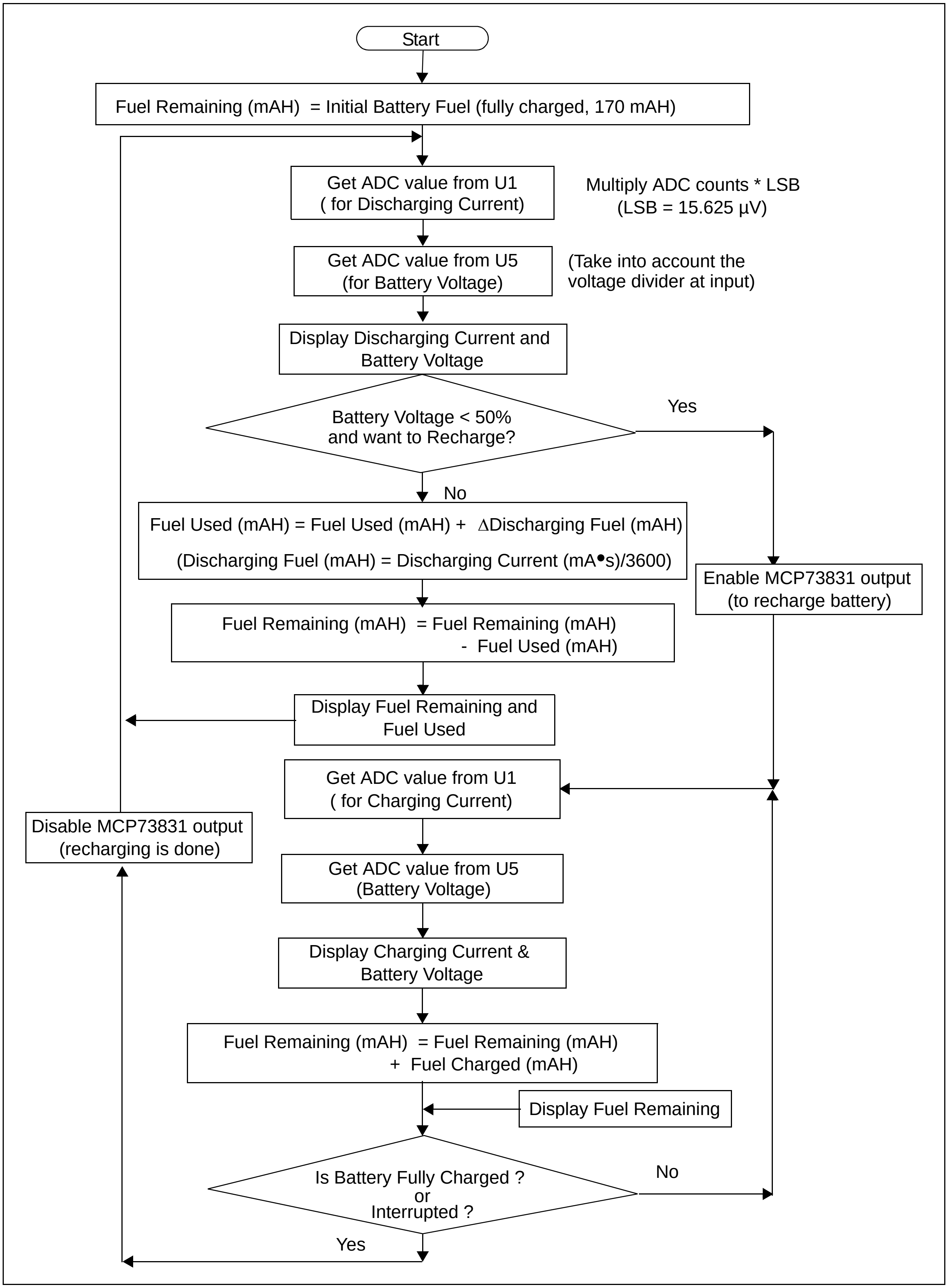

FIGURE 11: *Battery Fuel Management Algorithm.*

CONCLUSIONS

The battery fuel gauging is relatively simple task if the device can keep track the current out of the battery (discharging current) and to the battery (charging current). The accuracy in the battery fuel gauging is depending on the accuracy of the current measurement. The stand-alone MCP3421 ADC family device provides much higher measurement accuracy than the ADC used in typical integrated fuel gauge devices. Beside its performance, it is also much cost saving choice.

The MCU firmware examples that are needed for realizing the fuel gauging algorithm are shown in the attachment. The MCU firmware are based on the PIC18F4550. The examples include many valuable codes such as reading and writing of the MCP3421 ADC device, binary multiplications, divisions, binary to decimal conversion for LCD display, etc.

The examples given in this application note do not include the temperature effect on the battery characteristics.

Note:	The MCU firmware example shown in the attachment is only valid for the specified battery type. The user needs to modify the firmware for other battery types.

REFERENCES

[1] MCP3421 Data Sheet, *"18-bit ADC with I²C Interface and On-Board Reference"*, DS22003, Microchip Technology Inc.

[2] MCP3421 Battery Fuel Gauge Demo Board User's Guide, DS51683A, Microchip Technology Inc.

[3] MCP73831/2 Data Sheet, *"Miniature Single-Cell, Fully Integrated Li-Ion, Li-Polymer Charger Management Controllers"*, DS21984, Microchip Technology Inc.

[4] PIC18F2455/2550/4455/4450 Data Sheet, DS39632, Microchip Technology Inc.

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