
Multiple Chemistry Battery Charger Solution Using the MCP1631HV PIC[®] Device Attach PWM Controller

*Author: Valentin C. Constantin
Microchip Technology Inc.*

INTRODUCTION

The history of modern day batteries began over two centuries ago when Alessandro Volta invented the first voltaic pile. Since then the batteries have become a common power source for industrial and consumer applications. We usually find them in portable media devices. Some of these batteries are rechargeable and require modern and intelligent electronic circuits for their charge and discharge management. Managing the batteries results in better energy efficiency and longer life.

Battery charger designs have advanced quickly over the last decade. New battery types with different chemistries have been created. These new chemistries required special charging profiles that were not available with conventional battery chargers. Previous complex power-management systems were developed using high-speed analog pulse-width modulation (PWM) circuits combined with digital logic and specialty analog-only circuits. They were application specific off-the-shelf solutions available for most applications. They had neither the features nor the flexibility to meet specialized requirements. Modern power-management applications have advanced from simple current and voltage regulators towards mixed signal applications utilizing programmable microcontrollers. The combination of a programmable microcontroller and high-speed PWM allows a designer the benefits of programmability and customization. The microcontroller can adjust the output current, voltage, switching frequency, duty cycle, soft start, and handle system faults when external conditions warrant a change. Programmable battery chargers have the ability to charge different battery pack chemistries without changing any of the circuit hardware. Firmware is used to handle the differences between the battery chemistries and their respective charge profiles.

This document will cover the recharging of Nickel Metal Hydride (NiMH), Nickel Cadmium (NiCd) and Lithium Ion (Li-Ion) batteries. It will also cover the recommended charge profiles for the NiMH/NiCd and Li-Ion battery chemistries.

The design example used in this application note is a DC-DC converter using the single-ended primary inductive converter (SEPIC) topology. The low-cost SEPIC design will concentrate on the use of Microchip's MCP1631HV high-speed PWM device and the PIC16F616 8-bit microcontroller. The firmware source code for this application note is available to download from the Microchip web site. The firmware is for the "MCP1631HV Digitally Controlled Programmable Current Source Reference Design" evaluation board. The firmware is programmed in C language using the MikroElektronika mikroC compiler for PIC[®] microcontrollers.

Charge Algorithms for Different Chemistries

This section covers several battery chemistry charge profiles. When a designer starts to develop a battery application, the first question regarding the battery management is: "What is the appropriate charge algorithm for this battery?" Different chemistries have different charge profiles, and different manufacturers have different recommendations when it comes to restoring energy. This application note covers the Nickel Metal Hydride (NiMH), Nickel Cadmium (NiCd), and Lithium Ion (Li-Ion) algorithms.

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RECOMMENDED NiCd/NiMH CHARGE PROFILE

NiCd/NiMH cells may be rapid charged at a 1C rate when the cell voltage is between 0.9V and 1.8V. They may be rapid charged at room temperature with a maximum current of 1C, where 1C is the capacity rating of the battery. The rapid charge rate may be between 0.5C and 1C. Charging batteries at more than 1C will cause the internal battery temperature and pressure to increase beyond manufacturing limits, resulting in the failure of the battery. When the battery voltage is below 0.9V, a preconditioning charge should be applied. The preconditioning charge rate is typically 0.2C in order to avoid a large temperature rise. A complete NiCd/NiMH current charge profile with battery voltage and temperature is illustrated in Figure 1.

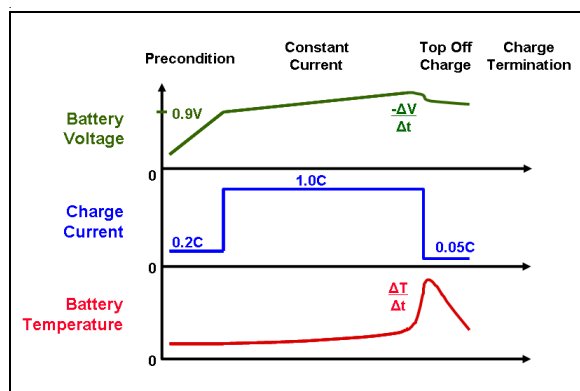


FIGURE 1: Typical NiMH and NiCd Charge Profile.

Charge termination for NiMH batteries typically uses voltage and temperature feedback. Two indications for determining when the battery has reached full charge are a rapid increase in temperature (dT/dt), and a small drop in battery voltage ($-dV/dt$). The $-dV/dt$ can be difficult to detect for the NiMH batteries since the change is very small. Lower charge rates result in a smaller $-dV/dt$ change. If an Analog-to-Digital Converter (ADC) is used for detection, the A/D converter must have enough bits of resolution to detect the small voltage change. The $+dT/dt$ temperature rise is typically easier to detect. The NiMH cells should have an NTC thermistor attached for temperature monitoring. Both the $-dV/dt$ and $+dT/dt$ methods should be used for a safe and robust design.

When the cell voltage drops 5 mV to 10 mV per cell during rapid charge, the system should switch to the charge Top Off mode. Rapid charge in Constant Current mode should also be terminated if the battery voltage exceeds 1.8V per cell, or if the temperature rises 1°C to 2°C within a 60 second interval. Top Off mode follows the Rapid Charge mode. Top Off mode is usually a one hour timed mode with the charging current set to a 0.05C rate. The total charge time for the battery should be limited to the one hour Top Off time plus the expected battery capacity divided by the charge rate. Fifteen minutes or a similar amount of time may be added to handle any pre-conditioning or other discrepancies that may come up during charging. Limiting the total charge time is necessary in case the cells fail to charge properly.

A summary flowchart that may be used as a starting reference for developing the firmware used to charge NiMH and NiCd cells is illustrated in Figures 2 and 3. This flowchart follows the charge profile presented in Figure 1. The program starts with the microcontroller initialization. All charging parameters (cell C rate, fast charging current, condition charge current, top off charge current, number of cells, etc.) are loaded during initialization. A safety timer (ChargeTimer) is used to prevent overcharging if the normal cell charge termination is not detected. The value of the charge timer may be up to 4 or 5 hours, depending on the cell capacity. A 1.8V overvoltage protection (OVP) per cell check will finish the charging if a cell is overcharged. The OVP condition is verified 5 times before shutting down the system. The cell overtemperature protection (OTP) will also be checked. The charge timer will be reloaded with 1 hour when entering Top Off mode.

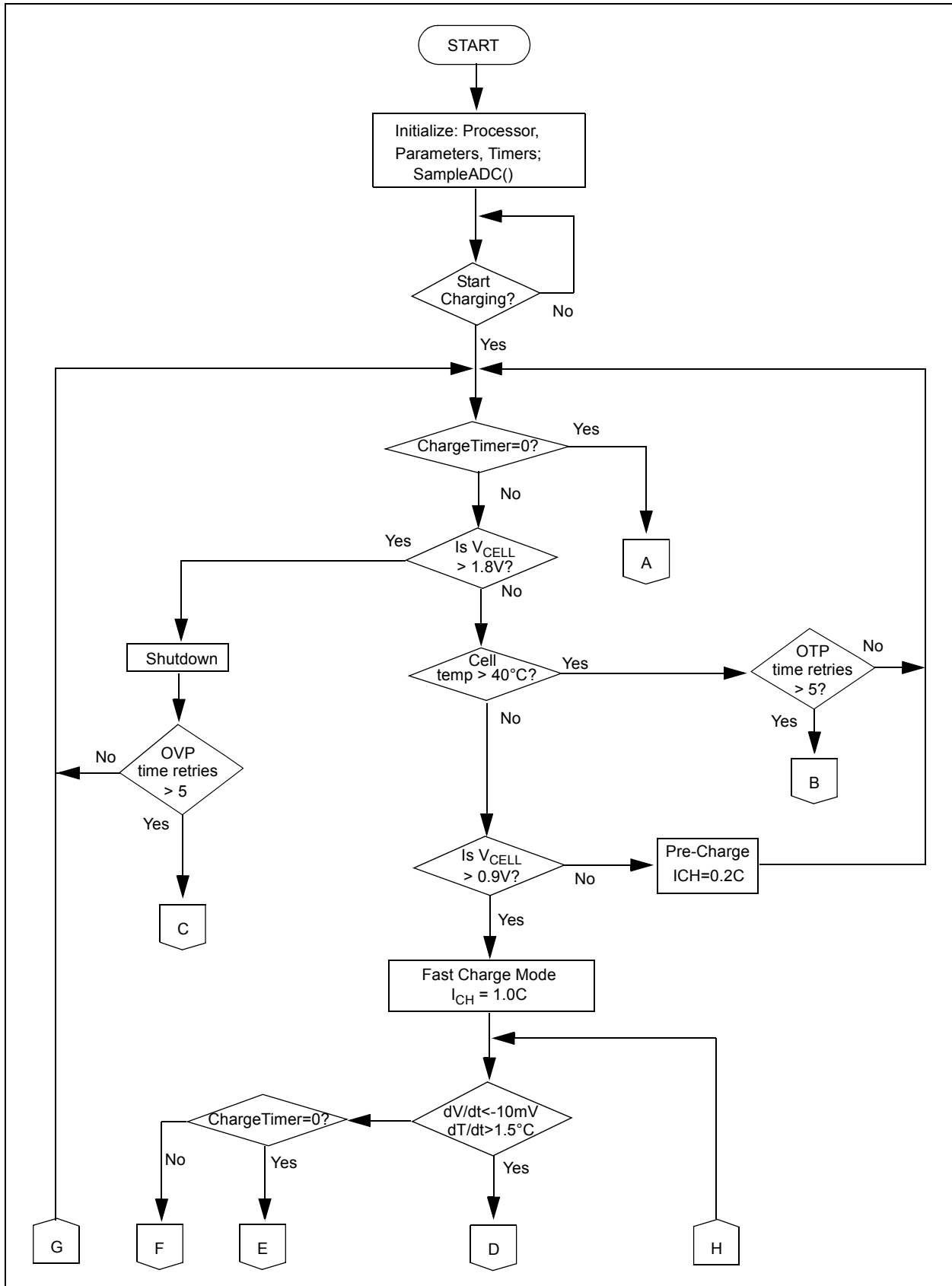


FIGURE 2: Example of NiMH/NiCd Charger Profile Flowchart.

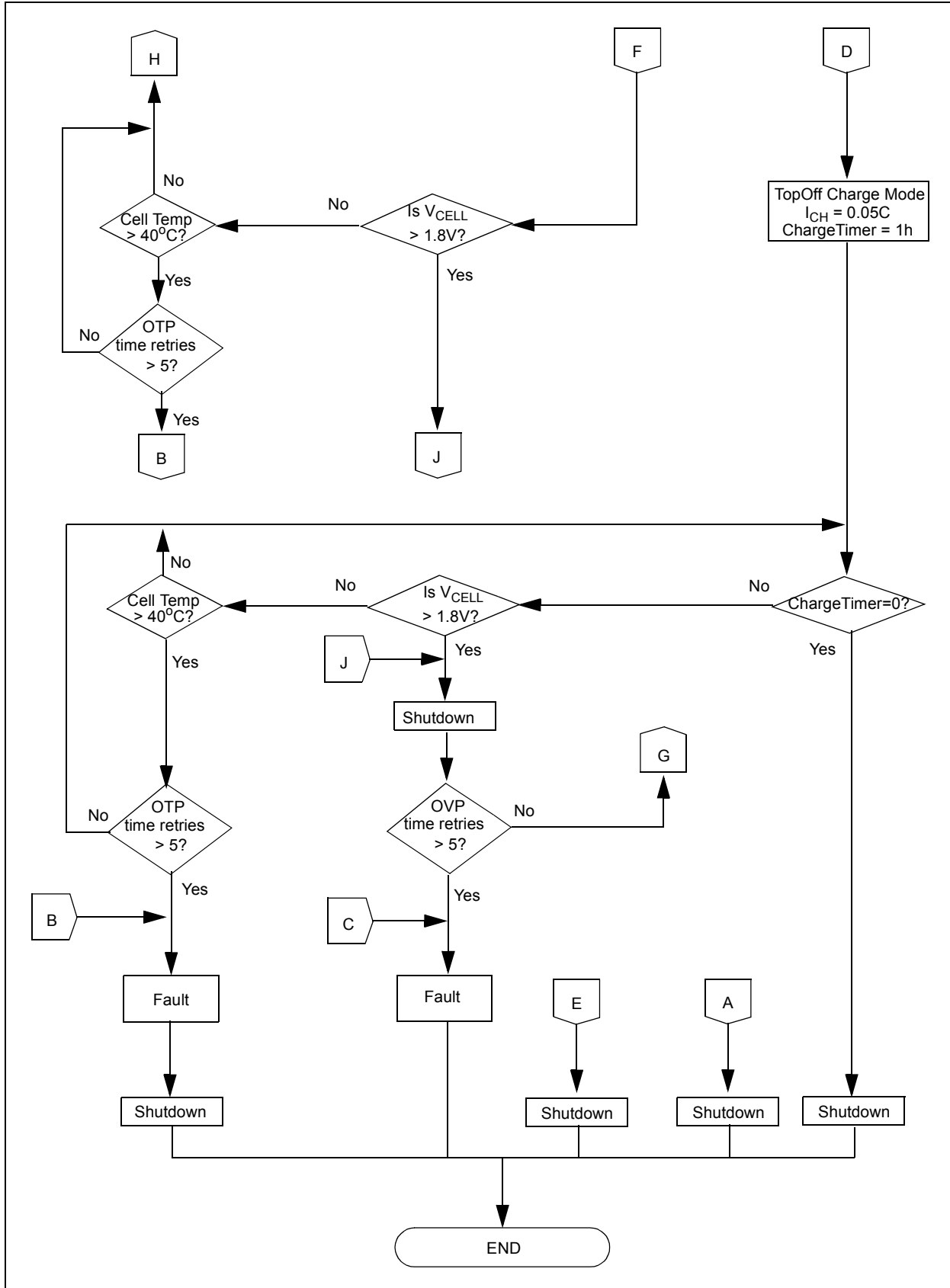


FIGURE 3: Example of NiMH/NiCd Charger Profile Flowchart (continued).

RECOMMENDED LI-ION CHARGE PROFILE

The preferred charge algorithm for the Li-Ion battery chemistry is illustrated in Figure 4. The charge profile for Li-Ion batteries starts with the cell qualification. When the cell voltage is below approximately 2.8V to 3.0V, the cell is charged with a constant current of 0.1C to 0.2C maximum. An optional safety timer (ChargeTimer, see flowchart in Figure 5) can be utilized to terminate the charge if the cell voltage does not increase.

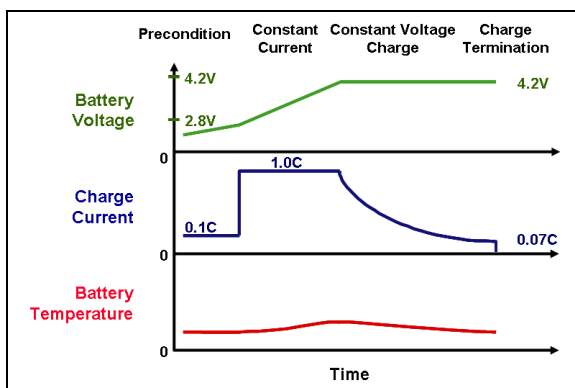


FIGURE 4: Typical Li-Ion Charge Profile.

Once the cell voltage is above the 2.8V to 3.0V qualification threshold, a fast charge at high current is initiated (0.5C to 1.0C). The cell is charged at a constant current rate while the cell voltage increases. The 3rd stage of charging—Constant Voltage mode—will start when the cell voltage level reaches 4.2V. The battery will continue to charge at the constant voltage level, while the charge current is gradually reduced to maintain the constant voltage level. When the charging current is reduced below 0.07C, the charge cycle is terminated. An optional safety timer should be utilized to terminate the charge cycle if no other termination method has been reached.

The constant-voltage set-point tolerance should be less than 1%. A small decrease in set-point voltage accuracy results in a large decrease in capacity. As an example a 1% undervoltage results in a 6% to 7% cell capacity loss. To avoid this loss, the set-point voltage for the cell should be calibrated. The flowcharts in Figures 5 and 6 are examples on how the calibration may be implemented into the firmware.

Charging is typically terminated by either the minimum charge current reached during the Constant Voltage mode, or by a safety timer.

Advanced chargers employ additional safety features. The charge will be terminated if the cell voltage exceeds approximately 4.3V or if the cell temperature is outside of a specified window. The overvoltage protection check should be validated multiple times before setting the OVP flag and terminate the charge cycle. Overcharging Li-Ion cells may result in sudden, automatic and rapid disassembly.

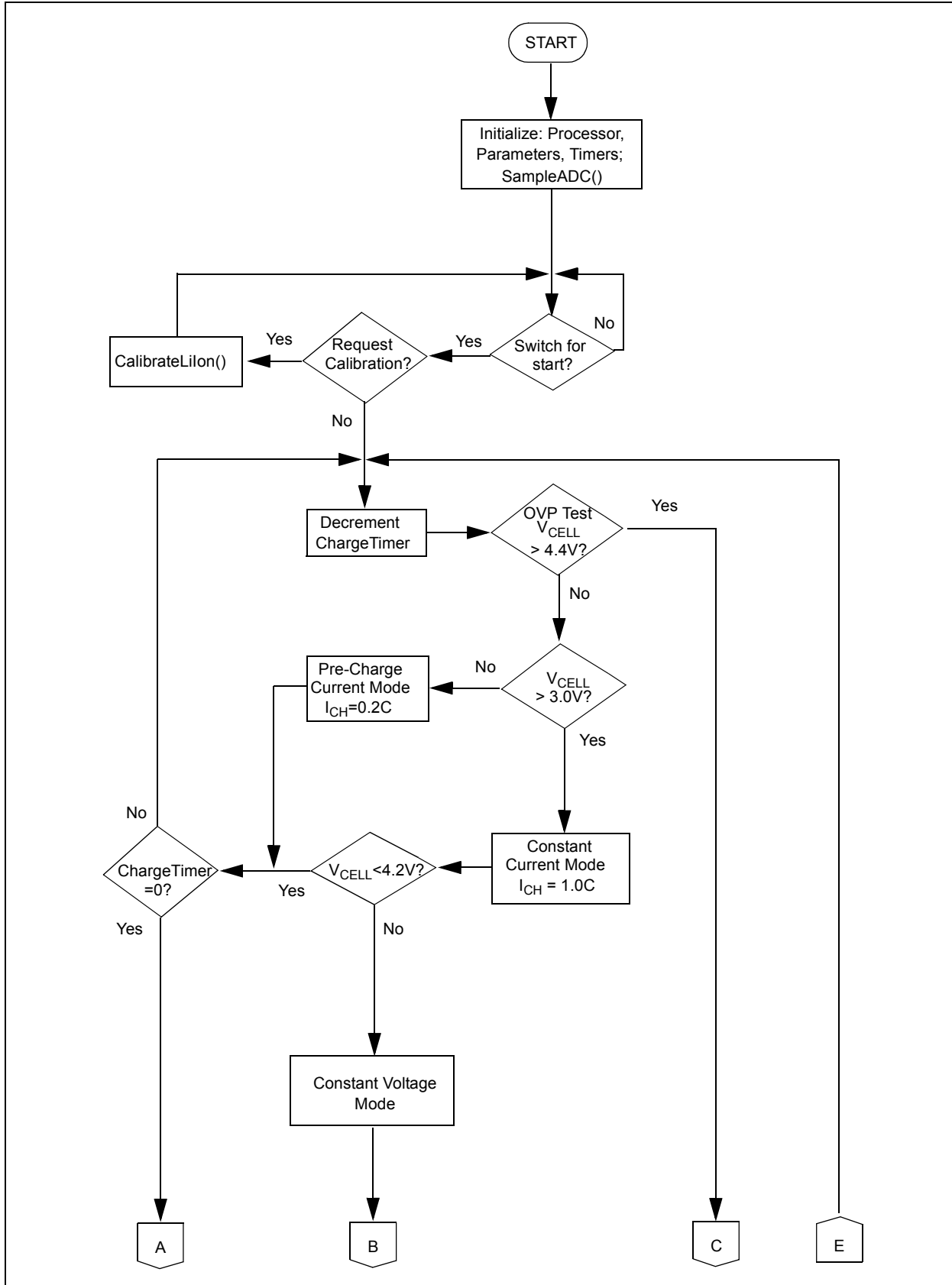


FIGURE 5: Example of Li-Ion Charger Profile Flowchart.

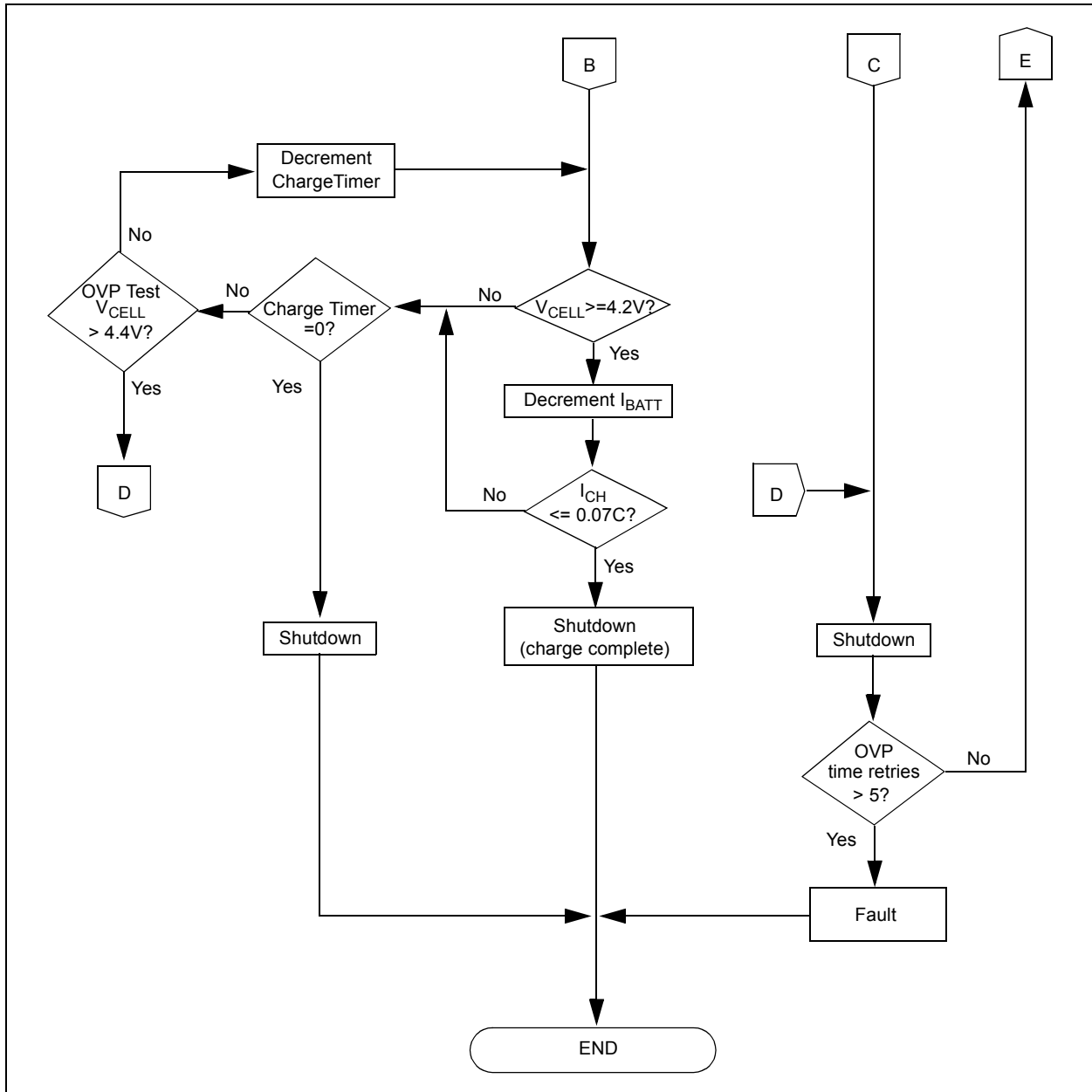


FIGURE 6: Example of Li-Ion Charger Profile Flowchart (continued).

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SEPIC POWERTRAIN TOPOLOGY

The single-ended primary inductive converter (SEPIC) topology is similar to a flyback design with the addition of a coupling capacitor between the two inductors. The output voltage may be less or greater than the input voltage.

This topology may use two inductors or a transformer with coupled windings. A capacitor connected between the windings offers DC isolation and protection against a shorted load. The capacitor clamps the winding leakage inductance energy, removing the need for a snubber circuit. The inductive input smooths the input current and reduces the necessary filtering. The load current may be sensed using a ground referenced sense resistor connected to the secondary winding.

The SEPIC converter is ideal for battery chargers because of the inherent DC isolation and the reverse voltage blocking rectifier at the output.

A typical SEPIC converter topology is shown in Figure 7.

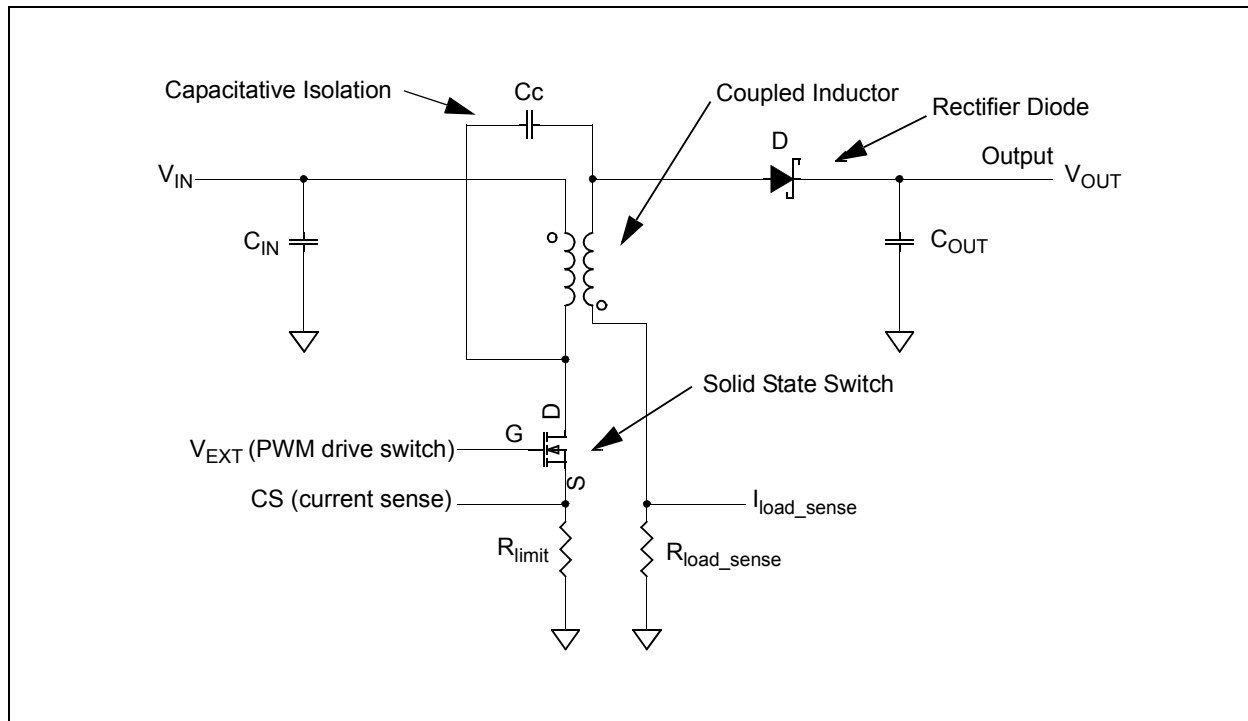


FIGURE 7: Single-Ended Primary Inductive Converter (SEPIC) Powertrain.

The waveforms in [Figure 8](#) are used to show how an SEPIC works.

L1 and L2 are equal in inductance and are wound on the same core. The NMOS switch (Q1) is turned on at the start of a cycle. The L1 inductor current (I_{L1}) starts ramping up at a rate of $V_{IN}/L1$.

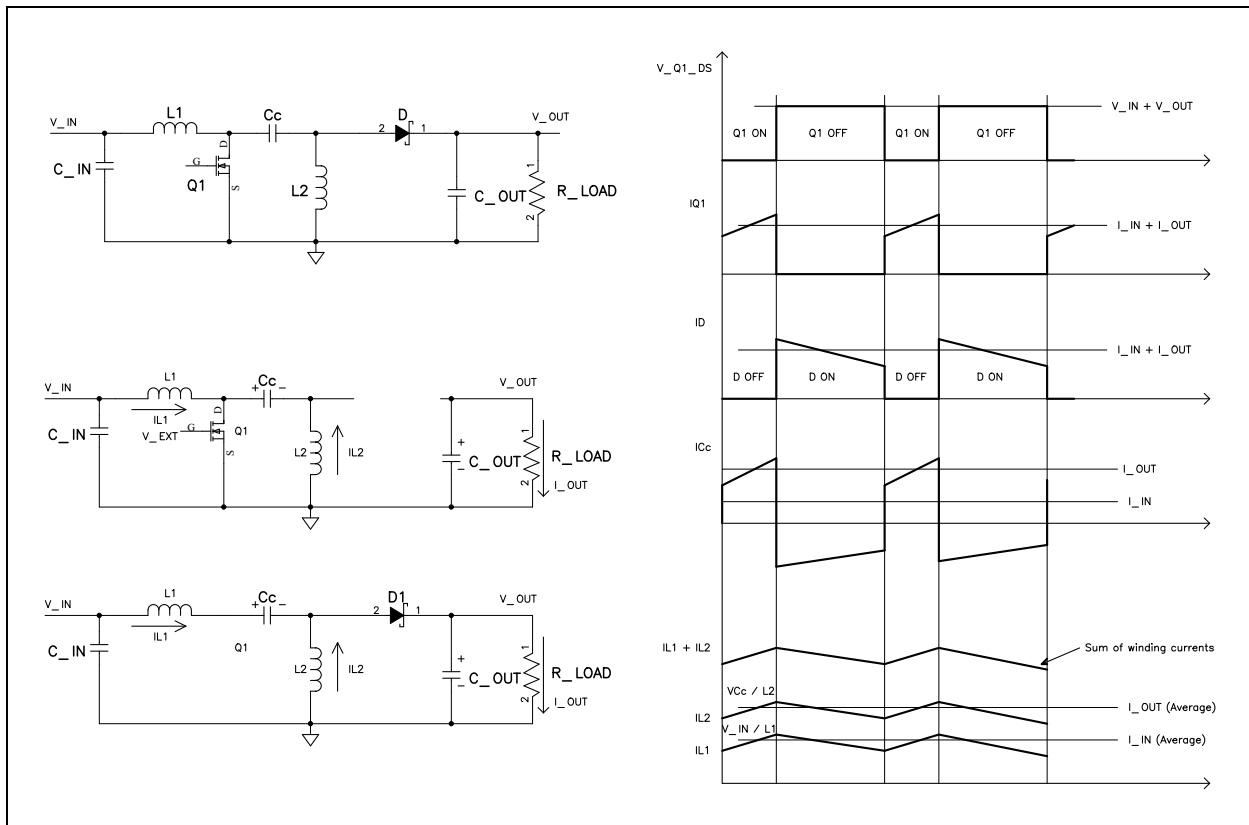


FIGURE 8: SEPIC Converter Waveforms.

The DC voltage across coupling capacitor V_{C_C} is equal to V_{IN} . The current in the secondary winding (L2) will ramp with $V_{C_C}/L2$ or $V_{IN}/L2$. The NMOS switch current is equal to the sum of the inductor currents I_{L1} and I_{L2} during the switch-on time.

When Q1 turns off, the path for current flow will change. With Q1 off the path for current is now from the input, through L1 and the coupling capacitor (Cc) to the output. Another path for the current flow exists through the secondary winding (L2) to the output. During the switch-off time the sum of L1 and L2 currents flow to the output through the rectifier. The current supplies the load and also replenishes the output capacitor (C_{OUT}).

Basic definitions for design are:

- T_{SW} = Switching Period
- f_{SW} = Switching Frequency
- t_{ON} = Switch-On Time
- t_{OFF} = Switch-Off Time
- Duty Cycle, $D = t_{ON}/T_{SW}$

The transfer function of the SEPIC converter in Continuous Current mode is:

EQUATION 1:

$$V_{OUT} = V_{IN} \times \left(\frac{D}{1-D} \right)$$

If the battery charging application has a low output voltage, the voltage drop (V_D) across the output rectifier diode should be considered. The voltage drop across a Schottky diode is about 0.3V to 0.5V. The maximum duty cycle (D_{max}) for an application will be:

EQUATION 2:

$$D_{max} = (V_{OUT} + V_D) / (V_{INmin} + V_{OUT} + V_D)$$

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The first step in calculating the inductor winding current is to determine the maximum output power. An efficiency estimate of 85% for the SEPIC topology may be used to approximate the input current. The average input current is equal to the input power divided by the input voltage.

EQUATION 3:

$$P_{OUT} = V_{OUT} \times I_{OUT}$$

EQUATION 4:

$$P_{IN} = P_{OUT} / (\text{Efficiency})$$

EQUATION 5:

$$I_{IN(AVG)} = P_{IN} / V_{IN}$$

When using a coupled inductor, the actual inductor will be half the value of L in Equation 6 due to the mutual coupling. The inductor value for the coupled windings is calculated by:

EQUATION 6:

$$\frac{L}{2} = V_{INmin} \times D_{max} / (2 \times \Delta I_L \times f_{SW})$$

where ΔI_L is the selected peak-to-peak ripple output current. A good ΔI_L selection is 20% of the output current.

Once the winding inductance (L) and duty cycle (D) are resolved, calculate the maximum inductor ripple and peak currents for L1 and L2 that will prevent saturating the inductors.

EQUATION 7:

$$\Delta I_{L1ON} = (V_{IN} \times t_{ON}) / L$$

EQUATION 8:

$$\Delta I_{L2ON} = (V_{Cc} \times t_{ON}) / L$$

Using $V_{Cc} = V_{IN}$ yields:

EQUATION 9:

$$\Delta I_{L2ON} = (V_{IN} \times t_{ON}) / L$$

The coupled inductor winding currents calculated below are used to determine the size of the inductor necessary.

EQUATION 10:

$$I_{L1peak} = I_{IN(AVG)} + \frac{1}{2} \Delta I_{L1ON}$$

EQUATION 11:

$$I_{L2peak} = I_{OUT(AVG)} + \frac{1}{2} \Delta I_{L2ON}$$

The switch current (I_{Q1}) is equal to the combination of the winding currents during the switch-on time: $I_{L1} + I_{L2}$. The peak Q1 switch voltage is equal to $V_{INmax} + V_{OUTmax}$.

The cathode of the SEPIC Schottky diode is connected to V_{OUT} and the anode of the schottky diode is connected to the SEPIC coupling capacitor. The voltage across the coupling capacitor is equal to V_{IN} . When Q1 is on, the voltage across the SEPIC diode is:

EQUATION 12:

$$V_D = V_{OUT} + V_{IN} = (V_{OUT} + V_{Cc})$$

To estimate the coupling capacitor capacitance, the capacitor derivative equation can be used:

EQUATION 13:

$$C_c = I_{Cc} \times \frac{\Delta t}{\Delta V}$$

For the SEPIC converter coupling capacitor, the voltage is approximated to be a DC value when deriving the duty cycle. The SEPIC capacitor must be rated for the RMS current. As output power increases, the capacitor ripple current will increase as well. This makes the SEPIC converter better for lower power applications where the RMS current through the capacitor is relatively small. The maximum RMS current in the coupling capacitor will occur at maximum output power and minimum input voltage.

EQUATION 14:

$$C_c = \left(\frac{I_{OUT}}{\Delta V_{Cc}} \right) \times \left(\frac{D_{max}}{f_{SW}} \right)$$

The ripple voltage (ΔV_{Cc}) should be no more than 5% of the voltage across the capacitor.

The same equation should be applied to the output capacitor. The output current is supplied by the output capacitor C_{OUT} during the switch ON time.

EQUATION 15:

$$C_{OUT} = \left(\frac{I_{OUT}}{\Delta V_{OUT}} \right) \times \left(\frac{D}{f_{SW}} \right)$$

The input capacitor C_{IN} should be capable of handling the input RMS current. The input current waveform is continuous and triangular. The inductive input ensures that the input capacitor sees low ripple currents from the power supply. The input capacitor provides a low-impedance source for the SEPIC converter in cases where the power source is not immediately adjacent to the SEPIC powertrain.

MCP1631HV AND SEPIC CONVERTER IN A MULTI-CHEMISTRY CHARGER APPLICATION

DESIGN EXAMPLE

MCP1631HV PWM Controller

The MCP1631HV integrates the necessary blocks to develop an intelligent programmable battery charger. It provides a regulated bias voltage for internal circuitry and external devices. It is available with two regulated output voltage options, +5.0V and +3.3V. The on-board regulator can supply a maximum output current of 250 mA. The maximum input voltage range for the regulator is +16.0V.

The MCP1631HV has an oscillator input pin (OSC_IN) that may be supplied by a microcontroller PWM output or by a simple clock output (50% duty cycle). When the oscillator input is high, the V_{EXT} output pin is pulled low (Figure 9).

When OSC_IN input transitions from a high to a low level, the internal N-channel MOSFET driver will turn off and the P-channel MOSFET will turn on, driving the V_{EXT} pin high. The V_{EXT} pin connects to the gate of an external N-channel MOSFET. The MOSFET will turn on when the V_{EXT} pin goes high. Current begins to ramp up in the external CS sense resistor until it reaches one third of the level of the error amplifier output voltage, which is limited to 0.9V by an error amplifier clamp. The 0.9V limit is used as an overcurrent limit. A filter is used on the CS input to remove the spikes associated with the turn on of the external power MOSFET. The MCP1631HV P-channel driver MOSFET is powered using a separate PV_{DD} pin to keep switching noise off on AV_{DD} pin and sensitive CS circuitry.

Any difference between the V_{REF} and V_{FB} inputs of the A1 error amplifier are quickly removed. If the V_{FB} input is high, the inverting error amplifier output (COMP) will be pulled down. The peak current into the switch will be lowered, and the duty cycle will be shortened in order to bring the output back into regulation. The external R and C used for compensation are used to control the speed of the error amplifier output response. If not compensated properly, the error amplifier output may be underdamped (oscillations) or overdamped (slow response). The V_{REF} input may be set by a microcontroller to program the proper charge current.

The SEPIC topology does not require a current sense resistor to be connected directly to the battery because the current into secondary winding is equal to the current flowing into the battery. A sense resistor will be used to sense the secondary current. The MCP1631HV integrates a 10 V/V gain inverting amplifier for buffering the battery current sense signal.

The battery voltage is sensed using the A/D converter of the PIC16F616 microcontroller. The MCP1631HV device integrates a low-current amplifier (A3), configured as a unity gain buffer. The amplifier is used to buffer the battery voltage sense signal, allowing the use of high value resistors in the battery voltage feedback divider network.

Overvoltage (OV) protection is required for any current source application. The MCP1631HV device integrates an internal high-speed OV comparator which has a 1.2V reference. If the voltage on the OV_IN pin exceeds the 1.2V threshold, the V_{EXT} output is asynchronously terminated. Switching will resume after the voltage has dropped by more than hysteresis value of 50 mV. If a battery is removed during the charge cycle, the charger output voltage will be limited to a safe value by the OVP circuitry.

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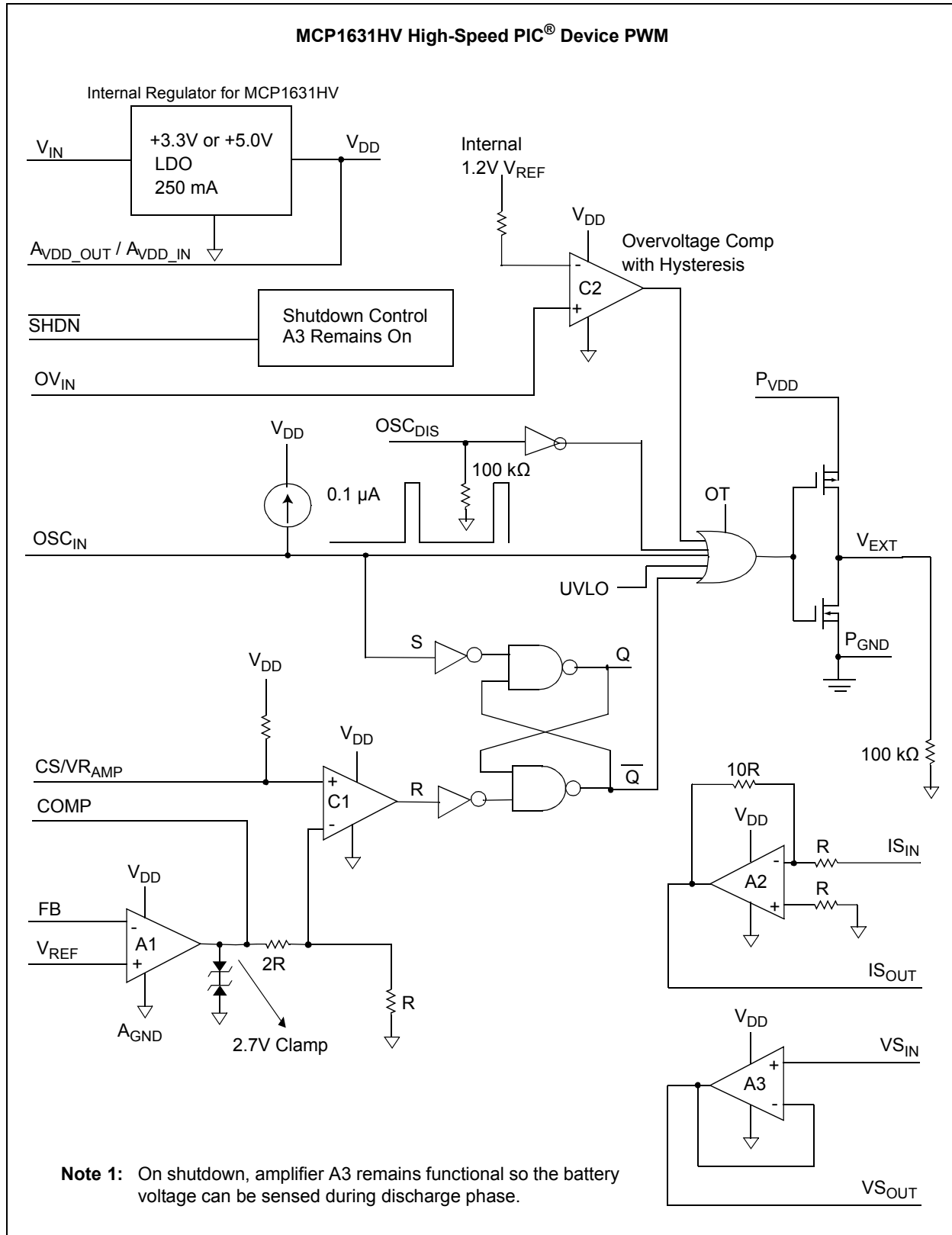


FIGURE 9: MCP1631HV PWM Controller – Functional Block Diagram.

Charger Reference Board Design

Microchip has developed a reference design board for dimmable power LED lighting and multi-chemistry battery charger applications to demonstrate the capability of the MCP1631HV PWM Controller.

The MCP1631HV Digitally Controlled Programmable Current Source (MCP1631RD-DCPC1) Reference Board is capable of driving 1A maximum at 8.5W output power. Efficiency is typically 85% at maximum power.

The board uses the PIC16F616 microcontroller to generate the proper dimming ratio for an LED or to generate the proper charge algorithm for Li-Ion or NiCd/NiMH batteries. The charge profiles for a specific battery may be obtained by downloading the firmware source code from Microchip's web site. The profiles may be modified for the users needs by changing the system parameters in the header file. The source code is then compiled and downloaded to the development board. A Microchip MPLAB[®] ICD 2/PICkit[™] 2 compatible programming header is available for updating the reference board firmware contained within the PIC16F616. The user may re-configure and compile the source code for Li-Ion or NiMH/NiCd battery charging instead of LED driving. The firmware packet has several files for LED dimming and battery charging as we will see in the next section.

The MCP1631HV Programmable Current Source Reference Board has the following features:

- Input Operating Voltage Range: +3.5V to +16V
- Optional battery charger software on the Microchip web site for charging Li-Ion, NiMH, and NiCd battery packs. Charge one or two single cell Li-Ion batteries in series or one to four single cell NiMH or NiCd batteries in series
- Maximum output capability for all modes of operation: 1A at 8.5W
- Status and fault indications with a dual color LED
- Default hardware and software overvoltage shutdown set at 9.0V

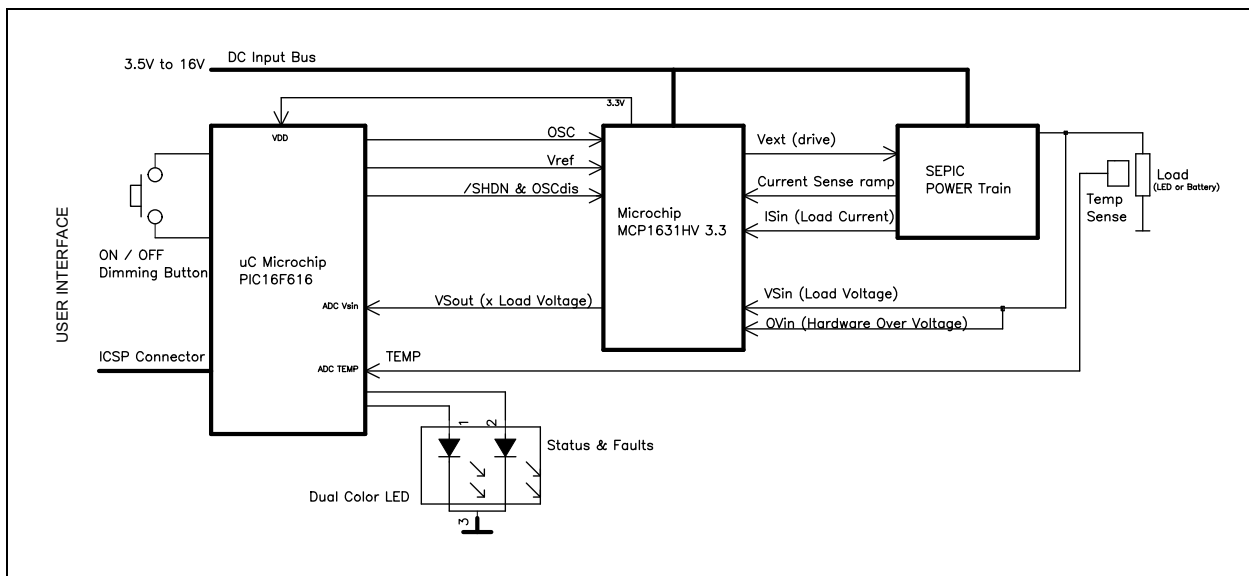


FIGURE 10: MCP1631HV Digitally Programmable Current Source Block Diagram.

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The MCP1631HV Digitally Programmable Current Source Reference Design has a red/green dual color LED (D2) to indicate status and faults. The green LED will flash for one second when the system is activated and current is being supplied to the load.

The push button (S1 in [Figure 11](#)) is used to enable the output and start the charge algorithm according to the flowcharts presented in [Figures 2, 3, 5 and 6](#). Pressing S1 again will turn off the output current. If a Fault condition such as no load, overvoltage, or overtemperature is present when attempting to turn the output on, the system will stay off and the Fault condition will be indicated by the flashing red indicator LED. The faults are coded as follows:

- Thermal Shutdown – Red LED flashes at 1 Hz rate if an overtemperature of the LED case has been detected
- Overvoltage Shutdown – Red LED flashes at 2 Hz rate if an overvoltage or a missing/open load has been detected

An overvoltage/overtemperature Fault condition will be verified 5 times by the microcontroller firmware before the fault is validated and the system shuts down.

Two parallel resistors, R_{10} and R_{11} , are used to sense the MOSFET switch (Q_1) current ([Figure 11](#)). The current sense signal is applied to the CS comparator input of MCP1631HV. The load current is equal to the current in the secondary inductor L1:B. Sense resistors R_2 and R_3 are used to sense the load current. The load sense signal is amplified by the $I_{S_{in}}$ current sense amplifier before entering the feedback pin (FB). A reference voltage signal from the PIC16F616 supplies the V_{REF} current reference voltage for the MCP1631HV. The pulse-width modulated V_{EXT} signal that drives the MOSFET switch is generated by the MCP1631HV device using the microcontroller current reference PWM signal and the load current feedback signal. The current feedback signal is integrated with the current reference signal. The integrated signal is compared with the switch current sense and an artificial compensation ramp to modulate the switch drive signal. The artificial compensation ramp is generated from the PIC16F616 OSC output signal to prevent the system from switching between continuous and discontinuous operation. The bi-modal operation would cause the duty cycle to vary when $D > 50\%$. The artificial ramp voltage supplements the switch current sense voltage to ensure the CS signal rises above the reference signal before the end of the integrator period. The MOSFET switch will be turned off when the CS signal rises above the reference signal and resets the integrator. The artificial ramp slope for the SEPIC will be the same as the slope of the current during the OFF time of the oscillator. The artificial ramp circuit block consists of C_{10} , R_9 , R_{13} and Q_2 , which is driven with the OSC signal.

A resistor divisor network composed of R_5 , R_8 and R_{15} is used for load voltage sensing. R_5 senses overvoltage conditions. R_8 senses the load voltage. The load voltage tap at R_8 is connected to the MCP1631HV internal voltage follower amplifier via the $V_{S_{IN}}$ pin. The corresponding $V_{S_{OUT}}$ signal is fed to the PIC16F616 A/D RA2 port.

When a thermistor is used, it is placed across J2-4 and J2-5. The thermistor forms a voltage divider with R_1 , a 10K resistor. The voltage across the thermistor is fed to the A/D port RA4 of the PIC16F616. If an overtemperature condition is detected, the microcontroller will disable the PWM signal of MCP1631HV.

The OSC signal is generated directly by the PIC16F616 PWM hardware at port RC5.

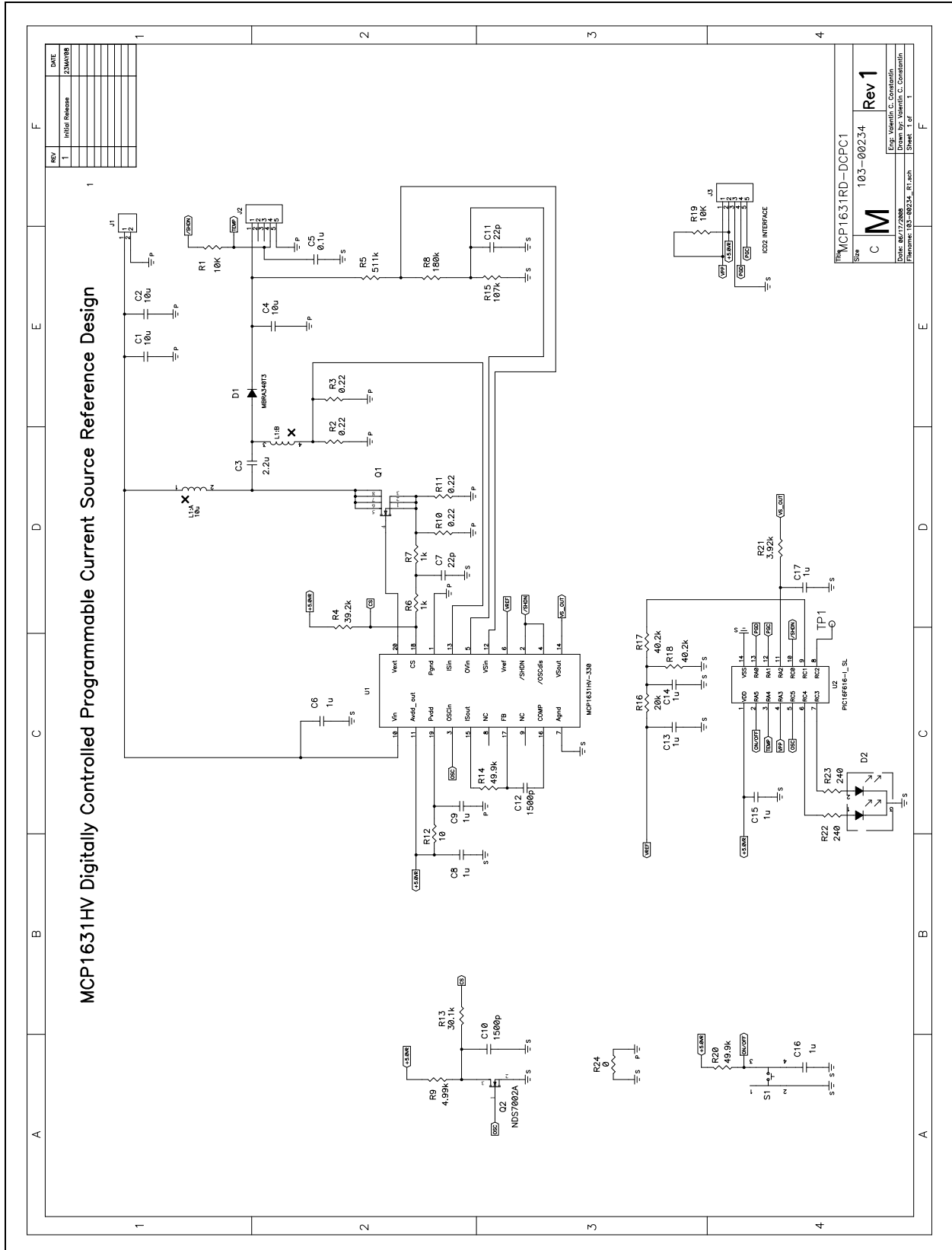


FIGURE 11: MCP1631HV Programmable Current Source Reference Design Schematic.

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The firmware is compiled with the following output capabilities:

- 1A output current for one Li-Ion cell or 500 mA for two series cells
- 700 mA for 1, 2 and 4 NiMH or NiCd cells

The charge profiles may be modified by editing and recompiling the source code that can be downloaded from Microchip's web site. The Gerber file for the MCP1631HV-DCPC1 Reference Board may also be downloaded from the Microchip web site.

MCP1631RD-DCPC1 Programmable Current Source Reference Design Firmware

The source code for Microchip's MCP1631HV Digitally Controlled Programmable Current Source Reference Design Board was developed using MikroElektronika's mikroC Compiler for PIC[®] Microcontrollers. The software has conditional compiler options for user selectable parameters and functions. The LED driver is the default compiler option. The NiMH/NiCd and Li-Ion battery charger options are selectable at compile time by modifying a parameter in the header file. The mikroC compiler may be downloaded from <http://www.mikroe.com>. Please consult the mikroC web site and compiler Help for more information.

The firmware packet has the following hex files:

- LED = 00234R1.hex
- Li-Ion = 00234R1-LiIon_Charger.hex
- NiMH/NiCd = 00234R1-NiMH_NiCd_Charger.hex

The C source code file is *00234R1.c* and the setup header file is *00234R1.h*. These two files are included in the mikroC project file: *00234R1.ppc*.

To modify the system profile, the user edits the *00234R1.h* file. Set the profile of interest for the reference board to "Enabled". The example below is for a single 1000 mAh Li-Ion cell:

```
/* Enable support for Lithium Ion batteries */
#define LION_SUPPORT EENABLED

/* Enable support for Nickel Metal Hydride batteries */
#define NIMH_SUPPORT DISABLED

/* Enable support for LED Driver */
#define LED_DRIVER_SUPPORT DISABLED
```

The charging current profile parameters are set in separate sections of the header file for the project. The cell overvoltage value is set to 200 mV by the parameter *LI_ION_OVER_VOLTAGE_CHARGE*. The 0.2C Li-Ion condition current value is set to 200 mA by the parameter *LI_ION_CONDITION_CURRENT*. The cell conditioning voltage set point is set at 3.0V by *LI_ION_CONDITION_VOLTAGE*. The maximum battery charge current in Constant Current mode is set to 1000 mA by the *LI_ION_CHARGE_CURRENT* parameter. The 0.07C charge termination point for Constant Voltage mode is defined as 70 mA by *LI_ION_CHARGE_TERMINATION_CURRENT*. The default number of cells to charge is set to 1 by *NUMBER_OF_CELLS_DEFAULT*. The overtemperature set point can be enabled or disabled by setting the *OVERTEMPERATURE_SUPPORT* parameter. The default overtemperature set point is +40°C. A 10K NTC thermistor inside the battery pack must be connected between J2-4 and J2-5 of the J2 connector (see the schematic in [Figure 11](#)) when the overtemperature feature is enabled.

```
#if (LION_SUPPORT == ENABLED)
//-----
// define the LiIon charge characteristics (in mil-
//ivolts and milliamps) for 1000mAh Cells
//-----
/* cell overvoltage charge = (150 mV to 200 mV) */
#define LI_ION_OVER_VOLTAGE_CHARGE
    ((int) (200.0/BATTERY_MV_PER_BIT))

/* cell conditioning current = 200 mA (0.2C) */
#define LI_ION_CONDITION_CURRENT
    ((int) (200.0/BATTERY_MA_PER_BIT))

/* cell conditioning voltage = 3.0V */
#define LI_ION_CONDITION_VOLTAGE
    ((int) (3000.0/BATTERY_MV_PER_BIT))

/* total charge current = 1000 milliamps max */
#define LI_ION_CHARGE_CURRENT
    ((int) (1000.0/BATTERY_MA_PER_BIT))

/* charge termination current = 70 mA (0.07C) */
#define LI_ION_CHARGE_TERMINATION_CURRENT
    ((int) (70.0/BATTERY_MA_PER_BIT))

#define OVERTEMPERATURE_SUPPORT DISABLED

/* default number of cells */
#define NUMBER_OF_CELLS_DEFAULT 1

#endif /* LION_SUPPORT */
```


The OSC reference signal supplied to the MCP1631HV PWM controller is set by the PIC16F616. The frequency may be set to 200 kHz or 500 kHz. The parameters are set in the main C file, *00234R1.c*. The OSC frequency is dependant upon the SEPIC inductance and load. The default values should not be changed for the reference board.

```
/* define Oscillator Output PWM frequency Prescale
Value for PR2 */
#define OSC_500KHZ_PR2_REG 0x03
#define OSC_200KHZ_PR2_REG 0x09
#define OSC_PR2_REG OSC_500KHZ_PR2_REG
```

The oscillator duty cycle is set to 25% if the SEPIC reference board must work in Buck-Boost mode. The 25% duty cycle allows the system to boost the output voltage. The parameter is in the *00234R1.h* header file.

```
/* charge oscillator duty cycle */
#define OSCILLATOR_DUTY_CYCLE 25
```

Design Example

This is an example design for two 500 mAh Li-Ion cells connected in series.

- Input Voltage, $V_{IN}=12V$
- Output Voltage range, V_{CELL} from 0 to 8.4V
- Fast charge current at 1.0C, $I_{CH}=500\text{ mA}$
- Switching frequency, $f_{SW}=500\text{ kHz}$

We start from Equation 2 calculating the maximum duty cycle using 0.4V for the voltage drop of a Schottky diode:

$$D_{max} = (8.4V + 0.4V) / (12V + 8.4V + 0.4V)$$

$$D_{max} = 42\%$$

Given the switching frequency $f_{sw} = 500\text{ kHz}$, t_{ON} is:

$$t_{ON} = D_{max} / f_{SW}$$

$$t_{ON} = 0.42 / (500\text{kHz})$$

$$t_{ON} = 840\text{ns}$$

Calculate Maximum Output Power:

$$P_{OUT} = V_{CELLmax} \times I_{CH}$$

$$P_{OUT} = 8.4V \times 500\text{mA}$$

$$P_{OUT} = 4.2W$$

The typical efficiency of a SEPIC converter in this power range, using a Schottky diode for the output rectifier, is around 85%. According to Equation 4 the input power is:

$$P_{IN} = (4.2W) / 0.85$$

$$P_{IN} = 4.94W$$

The average input current is equal to the input power divided by the input voltage (see Equation 5):

$$I_{IN(AVG)} = (4.94W) / (12V)$$

$$I_{IN(AVG)} = 412\text{mA}$$

The inductor value for coupled windings results from Equation 6. ΔI_L is the selected peak-to-peak output ripple current, which is 20% of the output current:

$$\Delta I_L = 500\text{ mA} \times 0.2 = 100\text{ mA}$$

$$(L/2) = (12V \times 0.42) / (2 \times 100\text{mA} \times 500\text{kHz})$$

$$(L/2) = 50.4\mu\text{H}$$

The inductance is calculated to be 50.4 μH . Select a standard inductor value of 47 μH . Choosing a lower value for the inductor will result in an increase of ripple current by over 20%. Attention must be paid to the inductor, not to saturate.

A 47 μH inductor looks like a 94 μH inductor for coupled inductors. Larger inductance reduces ripple current.

Next, we calculate the ripple and peak inductor currents.

The input and output inductor ripple current is equal to (see Equations 7 and 8):

$$\Delta I_{L1ON} = \Delta I_{L2ON}$$

$$\Delta I_{L1ON} = (12V \times 0.84 \times 10^{-6}\text{s}) / (94 \times 10^{-6}\text{H})$$

$$\Delta I_{L1ON} = 108\text{mA}$$

The peak input current is:

$$I_{L1peak} = I_{IN(AVG)} + (0.5)\Delta I_{L1ON}$$

$$I_{L1peak} = 412\text{mA} + (0.5)108\text{mA}$$

$$I_{L1peak} = 466\text{mA}$$

The peak output current ($I_{OUT(AVG)} = I_{CH}$):

$$I_{L2peak} = I_{OUT(AVG)} + (0.5)\Delta I_{L2ON}$$

$$I_{L2peak} = 500\text{mA} + (0.5)108\text{mA}$$

$$I_{L2peak} = 554\text{mA}$$

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A Würth® Elektronik WE-DD744878470 surface mount shielded power transformer is selected.

The switch current of the NMOS transistor (I_{Q1}) is equal to the combination of the winding currents during the switch-on time:

$$I_{Q1peak} = I_{L1peak} + I_{L2peak}$$

$$I_{Q1peak} = 1.02A$$

The peak switch voltage on the transistor and Schottky diode is equal to:

$$V_{SW} = V_{IN} + V_{CELL}$$

$$V_{SW} = 12V + 8.4V$$

$$V_{SW} = 20.4V$$

The peak NMOS switch current and peak switch voltage help to choose the proper devices. An N-channel MOSFET with $30V_{DS}$, $30m\Omega$, logic-level switch Si4346DY from Vishay Siliconix is selected. The average current through the output Schottky diode is equal to the output current (I_{CH}). A Schottky diode with a 30V or greater reverse-voltage rating is used.

The coupling capacitor is calculated using Equation 14:

$$I_{OUT} = I_{CH} = 500mA$$

$$\Delta V_{Cc} = 0.05 \times V_{IN} = 600mV$$

$$C_c = \left(\frac{500mA}{600mV}\right) \times \left(\frac{0.42}{500kHz}\right)$$

$$C_c = 0.7\mu F$$

A standard $1\mu F$ X7R 25V rated ceramic capacitor can be used. The coupling capacitor must also be able to handle the current flowing during switch on (t_{ON}) and off times (t_{OFF}). Use the RMS expression of a trapezoidal waveform to determine the RMS current of the coupling capacitor:

$$I_{CcRMS} = \sqrt{D \times (I_1^2 + I_2^2 + (I_1 \times I_2)) / 3}$$

where I_1 is the lowest waveform current and I_2 is the highest waveform current: $I_1 = I_{AVG} + (I_{ripple}/2)$ and $I_2 = I_{AVG} - (I_{ripple}/2)$.

For Q1 turned on $I_{AVG} = I_{OUT(AVG)}$ and $I_{ripple} = t_{ON} \times 2V_{IN}/(4L)$. For this case I_1 will be:

$$I_{1ON} = 0.5A + (0.84 \times 10^{-6}s(12V/94 \times 10^{-6}H))/2$$

$$I_{1ON} = 0.5A + 0.054A = 0.554A$$

and I_2 will be:

$$I_{2ON} = 0.5A - 0.054A = 0.446A$$

$$I_{CcRMS(ON)} = \sqrt{0.42((0.554^2 + 0.446^2 + 0.247)/3)}$$

$$I_{CcRMS(ON)} = 324mA$$

For Q1 turned off $I_{AVG} = -I_{IN(AVG)}$ and $I_{ripple} = t_{OFF} \times 2V_{IN}/(4L)$. As shown above I_1 and I_2 in this stage of switching will be:

$$I_{1OFF} = -0.412A + (1.16 \times 10^{-6}s(12V/94 \times 10^{-6}H))/2$$

$$I_{1OFF} = -0.412A + 0.074A = -0.338A$$

$$I_{2OFF} = -0.412A - 0.074A = -0.486A$$

$$I_{CcRMS(OFF)} = \sqrt{0.58((0.338^2 + 0.486^2 + 0.164)/3)}$$

$$I_{CcRMS(OFF)} = 315mA$$

The worst-case SEPIC coupling capacitor current is:

$$I_{CcRMS} = \sqrt{(I_{CcRMS(ON)}^2 + I_{CcRMS(OFF)}^2)}$$

$$I_{CcRMS} = \sqrt{(0.324^2 + 0.315^2)} = 453mA$$

Output capacitor selection:

$$\Delta V_{OUT} = 0.05 \times V_{CELL} = 420mV$$

$$C_{OUT} = \left(\frac{500mA}{420mV}\right) \times \left(\frac{0.42}{500kHz}\right)$$

$$C_{OUT} = 1\mu F$$

A standard $1\mu F$ X7R at 16V DC rating and low ESR ceramic capacitor can be used. During L1 charging the output current is supplied by C_{OUT} .

CONCLUSION

For applications that require intelligent power management solutions like battery chargers, the combination of a microcontroller and the MCP1631HV high-speed PWM is very powerful. It brings the programmable benefits of the microcontroller and adds the performance of a high-speed analog PWM. The analog PWM will respond to changes in input voltage and output current very quickly. The microcontroller is used for programmability, for establishing charge current, for monitoring the circuit for Fault conditions, and for taking the appropriate action in the event of a specific fault.

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