Author: Vladimir Veljkovic
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Introduction

This note describes the design of a complete charging circuit. A single cell Li-Pol battery is charged in two stages: Constant current (CC) until a voltage limit is reached, and then constant voltage, until the current is below a set threshold of about 10% of initial constant charge current. Li-Pol batteries are available in single cell, which is the common option in the mass market. Single cell LiPo chargers are integrated into many electronic devices such as cell phones and IoT products, together with the Li-Pol battery itself. Common options to power the charger are regulated +5 Volt power sources like USB power, AC wall adapter etc.

Li-Pol Battery Charging Process

Besides the main charging stages CC and CV, there are preconditioning, top off stage and maintenance mode. Preconditioning is needed when charging deeply discharged batteries. Such batteries are charged with low current (10% of full rate charge current) until battery voltage reaches 3.0V. Timed top off stage continues to charge the battery to provide optimal battery capacity following a complete charge cycle. During this cycle, charging terminates when ICHG reaches 2.5% of the full-rate charge current or when TTOPOFF times out, whichever occurs first. Once the top off stage is completed, maintanance mode monitors battery voltage and if the voltage drops below 4.0V a new charge cycle is initiated. Stages and transitions are presented in the Fig. 1 showing the different voltages associated with each state/state transition.

Specs and features

In this application note, we will focus on single cell Li-Pol charger powered from a regulated +5 Volt supply, like USB port power source. Since the power source is regulated and voltage dropout is relatively low, a linear charger circuit approach was chosen.

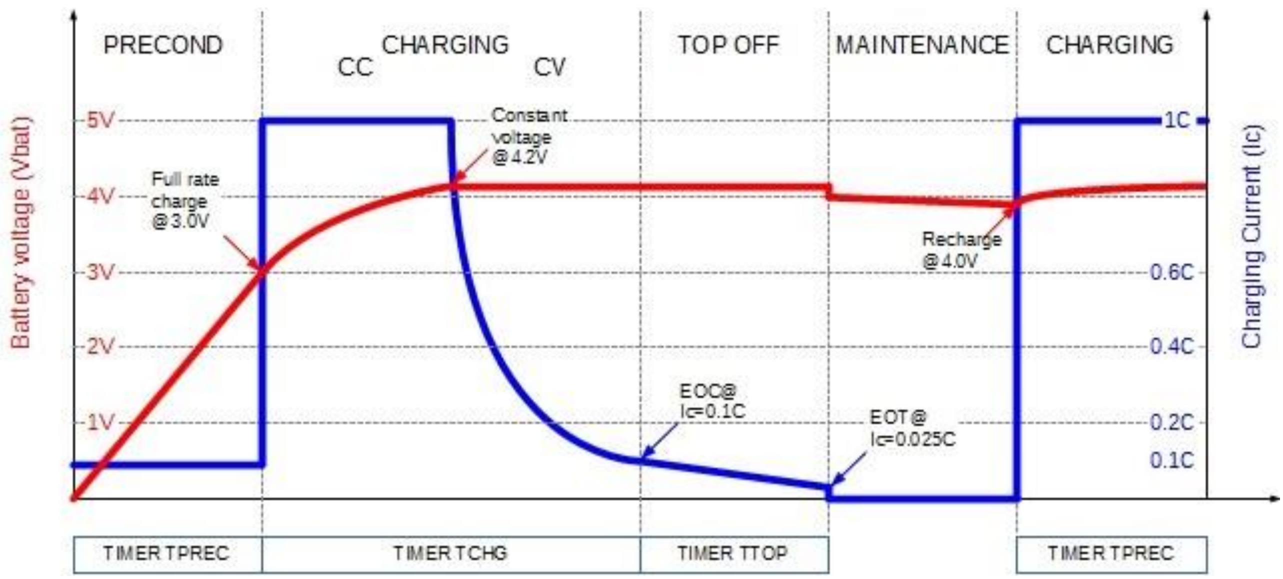

Figure 1. Li-Pol Battery Charging Process

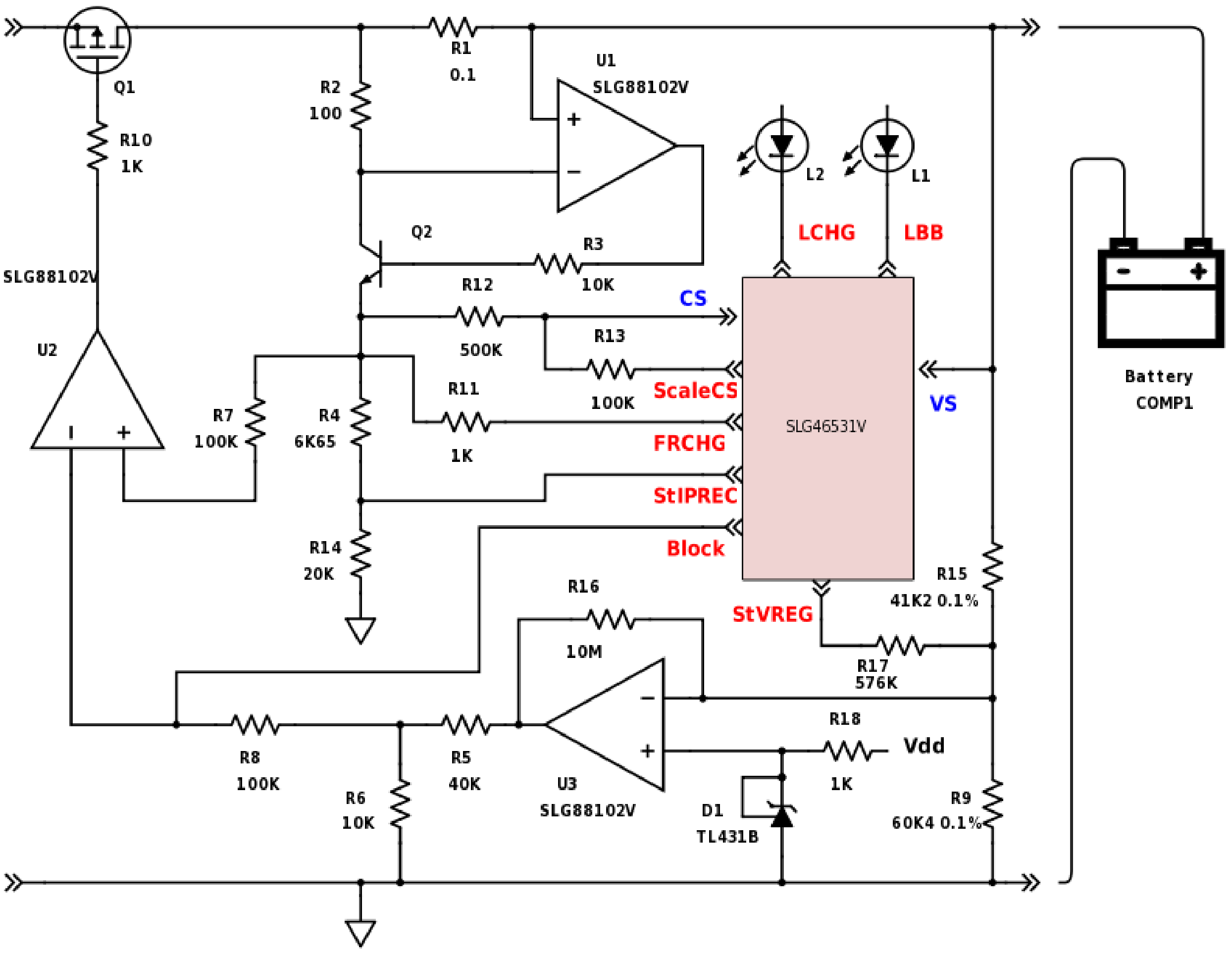

Figure 2. Schematic of power circuitry

It also minimizes EMI radiation and shielding requirements. To enable high charging currents, we employ a GreenPAK IC as the control circuit and external "power" circuit. The GreenPAK acts as "Li Pol Charge Management Controller", and features:

• Full rate charge current is programmed through an external resistor allowing charge currents up to 2500mA[1]

• High Accuracy Preset Voltage Regulation: 4.2V ± 0.75%, Settable to: 4.25V, 4.35V, 4.38V

• Built-in Multiple Safety Timers

• Charge Status Indication

• Continuous Over-current Protection

• Near-depleted Battery Pre-conditioning Settable to: 10%, 20%, 40% ICHG or Disable

• Maintenance Mode with Automatic Recharge

• End-of-Charge Control Settable to 5%, 10%, 15% or 20% ICHG

• Battery presence detection

• Bad battery detection and indication

1 Higher currents than 2500 mA can be achieved by replacing current sense resistor

Power Circuit

Following the schematic in Fig. 2: A logic level PMOS transistor is used as a pass transistor, enabling direct drive from low power OpAmp SLG88102V. A precision shunt resistor enables high side current sensing, conditioned and translated to ground reference using a simple current mirror OpAmp circuit. A standard precision reference (TL431B) is used to set the output voltage. The circuit is designed as a current limited voltage regulator and no control action is necessary for CC/CV stage transition. LED indicators are driven directly by the GreenPAK.

Output voltage 0.75% accuracy is achieved from TL431B (0.5%) and resistive divider with 0.1% precision resistors. If tighter tolerance is required, higher accuracy components may be selected to achieve it.

Current limit is set by the value of resistor R2 in the current mirror circuit, 100 ohms per Ampere. For example, for 2.5 Amps current limit, R2 = 250 ohms. Current sense resistor is 0.1Ω and voltage drop is small enough for currents up to 2.5 Amps. Above that, current sense resistor value should be lower to reduce voltage drop, for example 0.05Ω. For current sense resistor other than 0.1Ω, current mirror resistor R2 must be recalculated: R2 = ICHG * Rcs / 1mA. When selecting current sense resistor, don't forget to consider its power rating.

For charging currents up to 500mA (battery capacity 500mAh) no heatsink is needed for the pass transistor because power dissipation is less than 1W. Above that current, the pass transistor should be mounted on a heat sink to avoid overheating. Maximum power dissipation occurs at transition from preconditioning stage to full charge and makes roughly 1W for every 0.5Amps of charging current (6W @ 3Amps), worst case.

For maximum temperature rise of ΔT and battery capacity Cb, heat sink thermal resistance must be less than Rhs = ΔT / (2*Cb/1000). For example, ΔT=20°C and Cb = 2500mAh yields thermal resistance Rhs ≤ 20 / 5 = 4 °C/W.

Follow appropriate PCB layout rules such as wide/short traces for high current paths, and separate traces for voltage sensing.

GreenPAK Design

SLG46531V GreenPAK 5 is selected for this design because it offers Asynchronous State Machine Block and 4 analog comparators with abundant additional logic blocks. As shown in Fig. 3, the GreenPAK design is modular:

1) Analog module with analog comparators for battery voltage and charging current,

2) Control module based on GreenPAK ASM block

3) Timing module

4) Signaling module for light indicators control

5) Interface module for I2C serial communication

Analog module

Li-Pol Battery charging requires accurate battery voltage measurements with tight tolerances to work correctly and safely. That is why external voltage reference, voltage divider and low offset operational amplifier were used for that portion.

Current measurements are not nearly as critical as battery voltage measurements, and the same goes for voltage thresholds for stage transitions. GreenPAK internal comparators are fully up to those tasks and no external components are necessary.

To control Li Pol charging profile, at least 2 thresholds have to be implemented:

1a) preconditioning threshold (battery voltage at 3V)

2a) end-of charge threshold (charging current at 10%)

For additional charger functions: battery detection, maintenance mode / automatic recharge and top off mode, 3 more thresholds are needed:

1b) battery detection (output voltage over 4.5V)

2b) recharge threshold (battery voltage below 4.0V)

3b) end-of-topoff threshold (charging current at 2.5%)

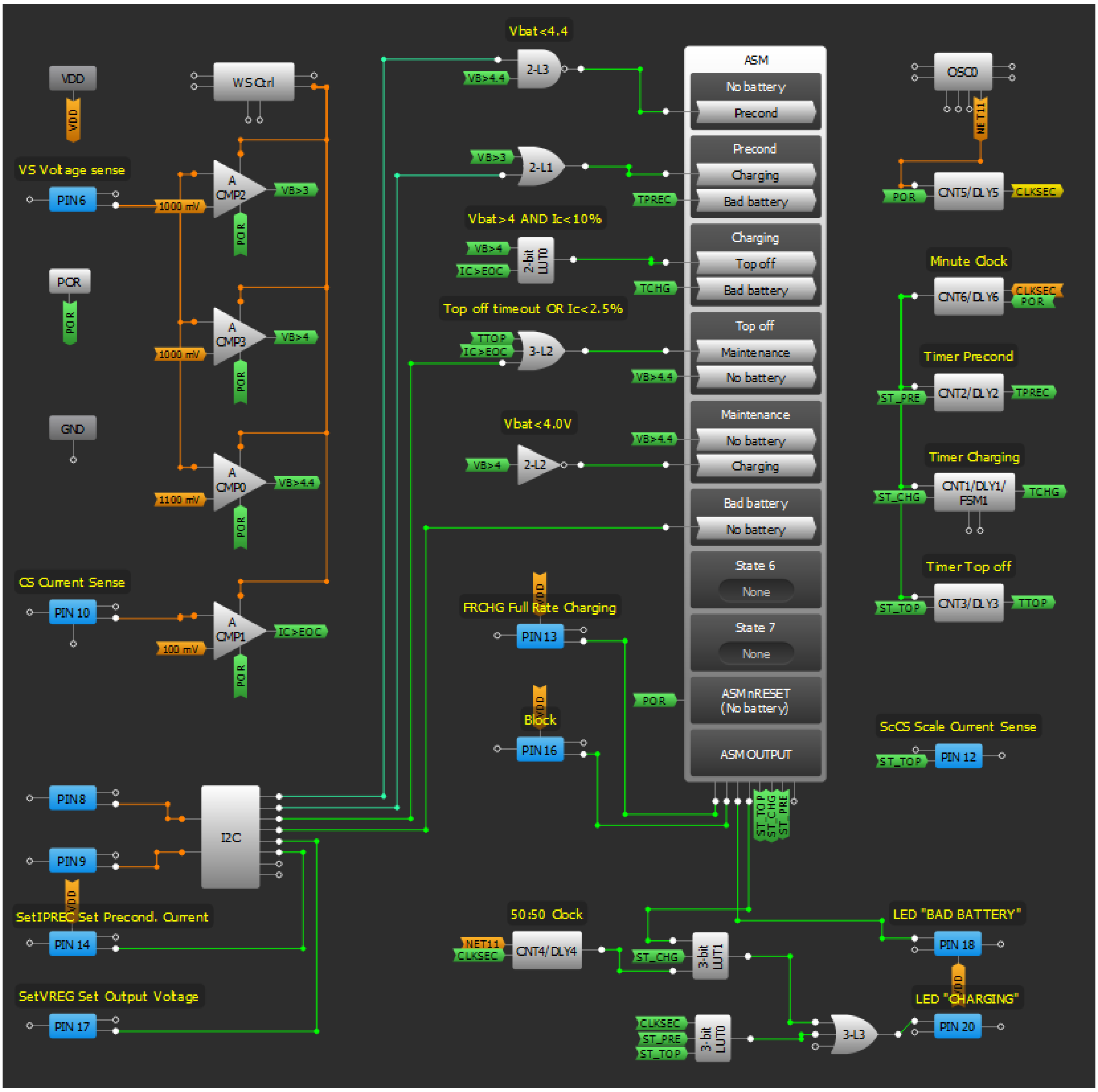

Figure 3. GreenPAK design schematic

Since SLG46531V has only 4 comparators, the 5th threshold for top off stage is realized by scaling the current sense signal once EOC is detected, during top off stage. ScCS signal switches off an additional resistor, decreasing the ratio of the current sense resistive divider, thereby increasing the current sense signal at GreenPAK input pin. Since the comparator threshold remains unchanged, charging current needs to decline further to reach the new threshold.

To avoid noise triggering issues, all comparators are programmed for with 25mV hysteresis.

Battery detection is based on a weak pullup resistor on the voltage sense input (VS pin). If no battery is connected, the pullup resistor will raise the voltage on comparator input to positive supply (5V), above the max limit of regular Li-Pol battery. When the battery is connected, it will define the voltage at VS pin and the small pullup current will not affect it.

Control Module based on GreenPAK ASM Block

The implementation of the control circuit is based on the state machine functionality of the GreenPAK. Out of 8 available states, 6 are used to capture the relevant states of the battery/charger, one for current limit level and one for blocking the charger.

2-bit and 3-bit LUT blocks are applied to form control signals for ASM state transitions.

State signals are named with ST_ prefix and further used in timing and signaling modules. They are active "1" when ASM is in the relevant state / charger in the relevant stage.

FRCHG signal sets the current limit to full rate. It is active in charging and top off stages. Block signal overrides the external circuit control loop and closes the pass transistor, thus stopping the charger. It is active in all states except the charging states of: preconditioning, charging, and top off.

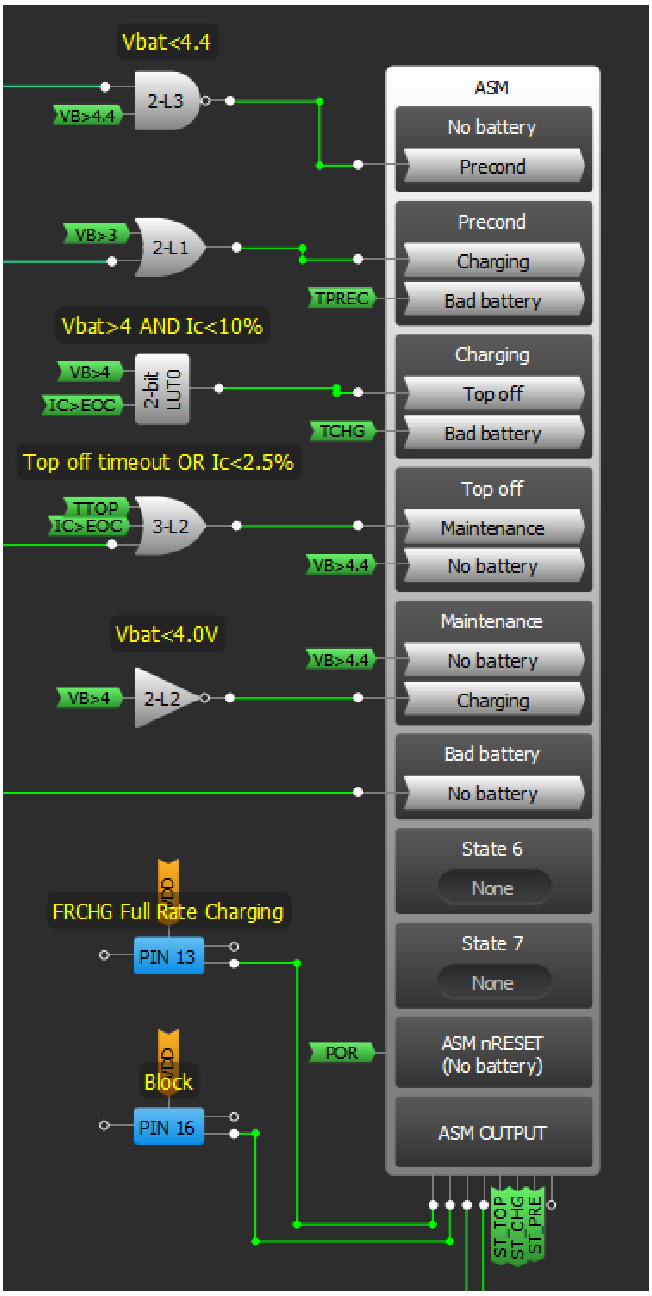

Figure 4. ASM Connections

Control module can be stopped by I2C command or by pulling down "Enable" pin. "Enable" pin has 100K pullup so the charger is enabled by default.

Enable/disable signals from I2C block control opening the LUT gates. This enables I2C control of the ASM transitions. I2C control signals are shown in Table 1:

Signal	Position	Default
Disable charger	I2C → OUT0	0, enabled
Disable preconditioning	I2C → OUT1	0, not disabled
Disable top off	I2C → OUT2	0, not disabled

Table 1. I2C control signals

ASM design

As shown in Fig. 5, three main states cover the three charging stages: preconditioning, charging and top off, while other states control no-charging periods. Initial ASM state is "No battery" because charger may be powered while no battery is connected to charger output. When the battery is connected, circuit will automatically detect battery presence and start charging. If the battery is not deeply discharged, the battery voltage will already be higher than 3.0V and ASM will immediately switch to full rate charging stage, otherwise that transition will happen later. If Preconditioning stage or Charging stage lasts too long, relevant timer will set ASM to "Bad battery" state.

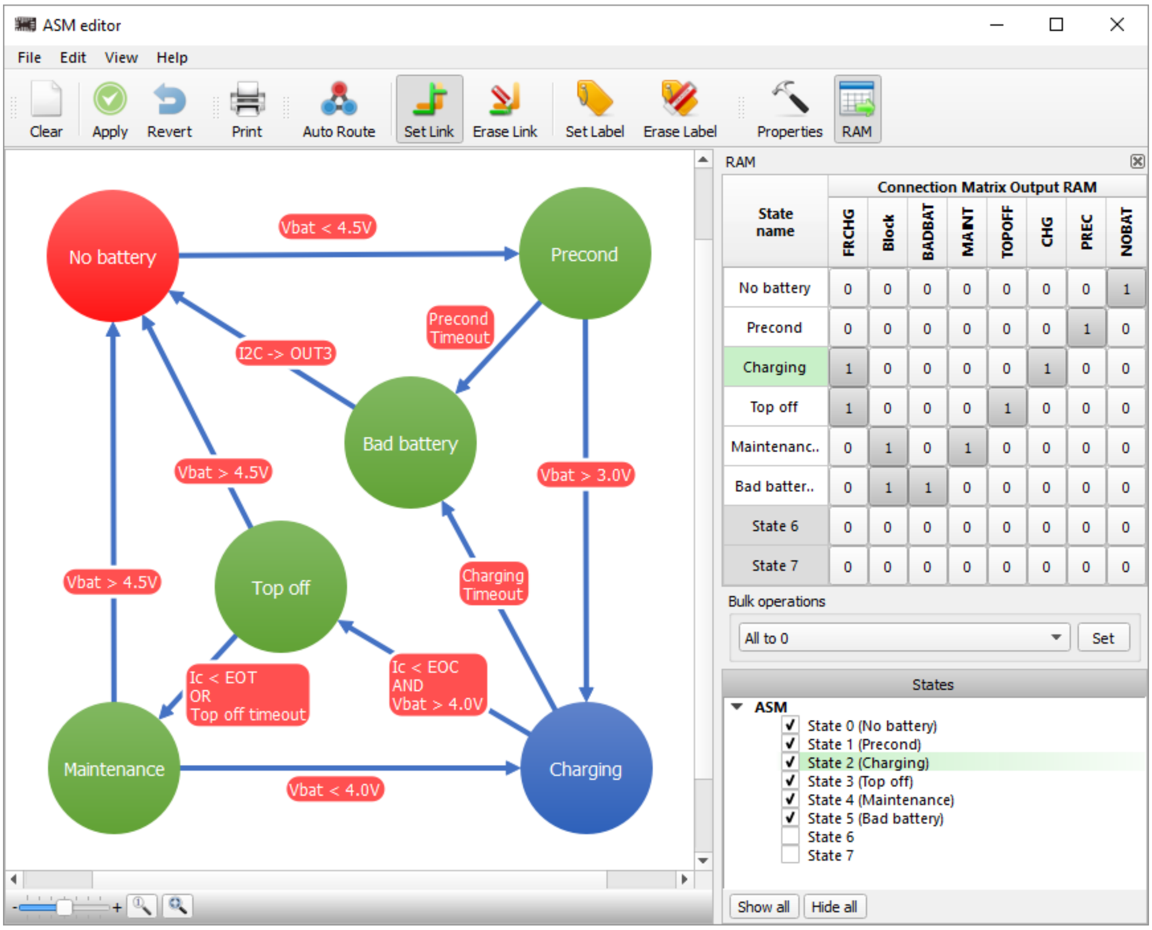

Figure 5. State diagram in GreenPAK

Once in this stage, the bad battery status may only be cleared by removing the input power source or by external command (I2C command "Disable charger" or pulling down the "Enable" pin).

Timing module

As shown in Fig. 6, the timing module includes clock circuitry that generates signals at second and minute intervals. The seconds clock is used for LED indicators, while minutes clock is used for safety timers.

Safety timers range from minutes to hours, so CNT/DLY blocks are used to implement timers for relevant stages, supplied by low frequency minutes clock. Minutes clock is generated by dividing 25kHz internal OSC frequency using two cascaded CNT/DLY blocks, with the first block forming the 1Hz (seconds) clock and the second block forming 1/60Hz (minutes) clock.

The timer starts upon relevant ASM output signal and asserts its output (TPREC, TCHG or TTOP) when timer expires.

The duration of safety timers is programmable by setting the counter values of relevant CNT/DLY blocks via the I2C block. Values are in minutes. Available range for preconditioning and top off timer is 8-bit (1 to 255), and for charging timer 16-bit (1 to 65535). Default values shown in Table 2 are:

Timer	Default	Range
Preconditioning	30 min	1-255 min
Charging	5 hours (300 min)	1-65535 min (1000hrs)
Top off	30 min	1-255 min

Table 2. Timer Default values

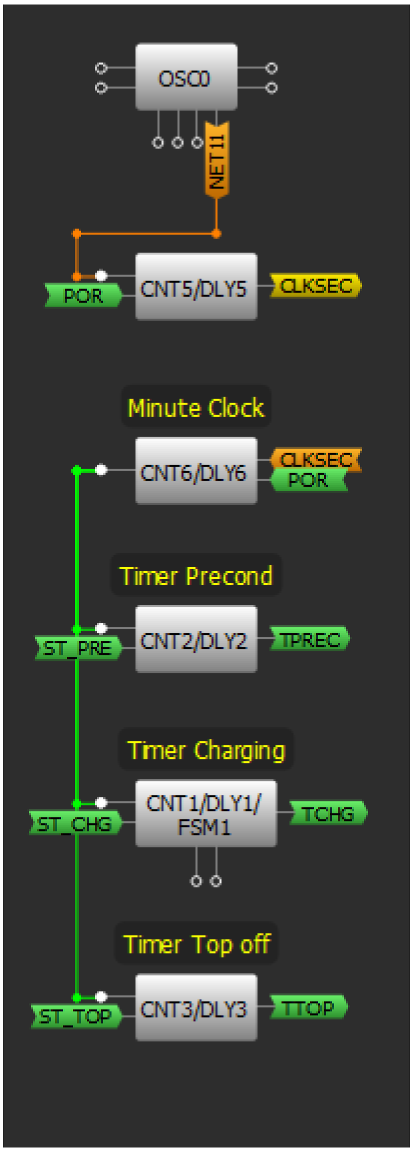

Figure 6. Timing Module Design

Indicators and signaling module

This circuit is for driving two LED's as indicators for status and operation. The Green LED "Charging" indicates all three charging states using pulse codes:

- short pulses: preconditioning stage
- 50:50 pulses: full rate charging stage
- long pulses (inverted short): top off stage

- on: maintenance mode (battery full)

- off: no battery

The Red LED "Bad battery" indicates error status if the battery attached is unusable or can't be fully charged. This indicator will also activate if, for example, a resistor is attached to the output instead of battery.

Fig. 7 shows the indicator circuit implementation using one CNT/DLY block and 3-bit LUTs. The CNT/DLY block is used to make symmetrical 50:50 signal from the 1Hz (seconds) clock, needed for indication of full rate charging mode. LUTs select the indication mode based on ASM state.

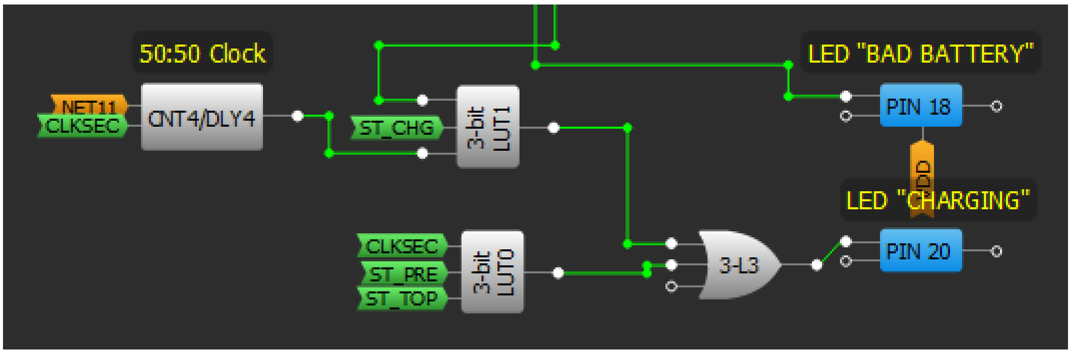

Figure 7. Charging indicator circuit

Output voltage	**4.2V**	**4.25V**	**4.35V**	**4.38V**
Pull down on StVREG pin	no	1MΩ	100KΩ	no
StVREG signal	off	off	off	on

Preconditioning	**10% ICHG**	**20% ICHG**	**40% ICHG**
Pull down on StIPREC pin	no	10KΩ	nm
StIPREC signal	off	off	on (open drain)

EOC	**5% ICHG**	**10% ICHG**	**15% ICHG**	**20% ICHG**
Pull down on CS pin	1MΩ	1MΩ	1MΩ	no
Pull down on ScCS pin	100KΩ	1MΩ	no	no
Divider ratio	1/4	~1/2 (0.51)	2/3	1
Divider ratio with ScCS on (top off stage)	0.15	0.15	0.15	0.17

Table 3. I2C programmable parameters

Interface module

The Interface module utilizes the GreenPAK I2C communication feature. It enables external signaling, for example, with an MCU or single board computer. Signaling enables programming charger parameters, controlling charger operation and monitoring the charging process.

Programmable parameters (as shown in Table 3): timer durations, enable/disable preconditioning stage, enable/disable top off stage, output voltage (4.2V, 4.25V, 4.35V, 4.38V), set preconditioning current level (10%, 20%, 40% ICHG), set end-of-charge threshold (5%, 10%, 15% or 20% ICHG)

Monitoring status: charger status by reading ASM state/output, stage duration by reading relevant timer (counter), pin status, readback current settings.

Performance

Main characteristics of the charger circuit are shown in table 4 below.

Testing the GreenPAK Design

The GreenPAK Emulation Tool included in GreenPAK Designer Development Suite was used to test this IC design (Fig. 8). Analog signal generators were used to simulate voltage and current sense inputs.

Custom signals were designed to cover all stages of a standard charging profile. Battery charging is a long process, so to enable efficient testing, each stage is accelerated to a simulated duration of 10 seconds. That is enough time to check relevant control signals and still one full test cycle is less than 2 minutes long.

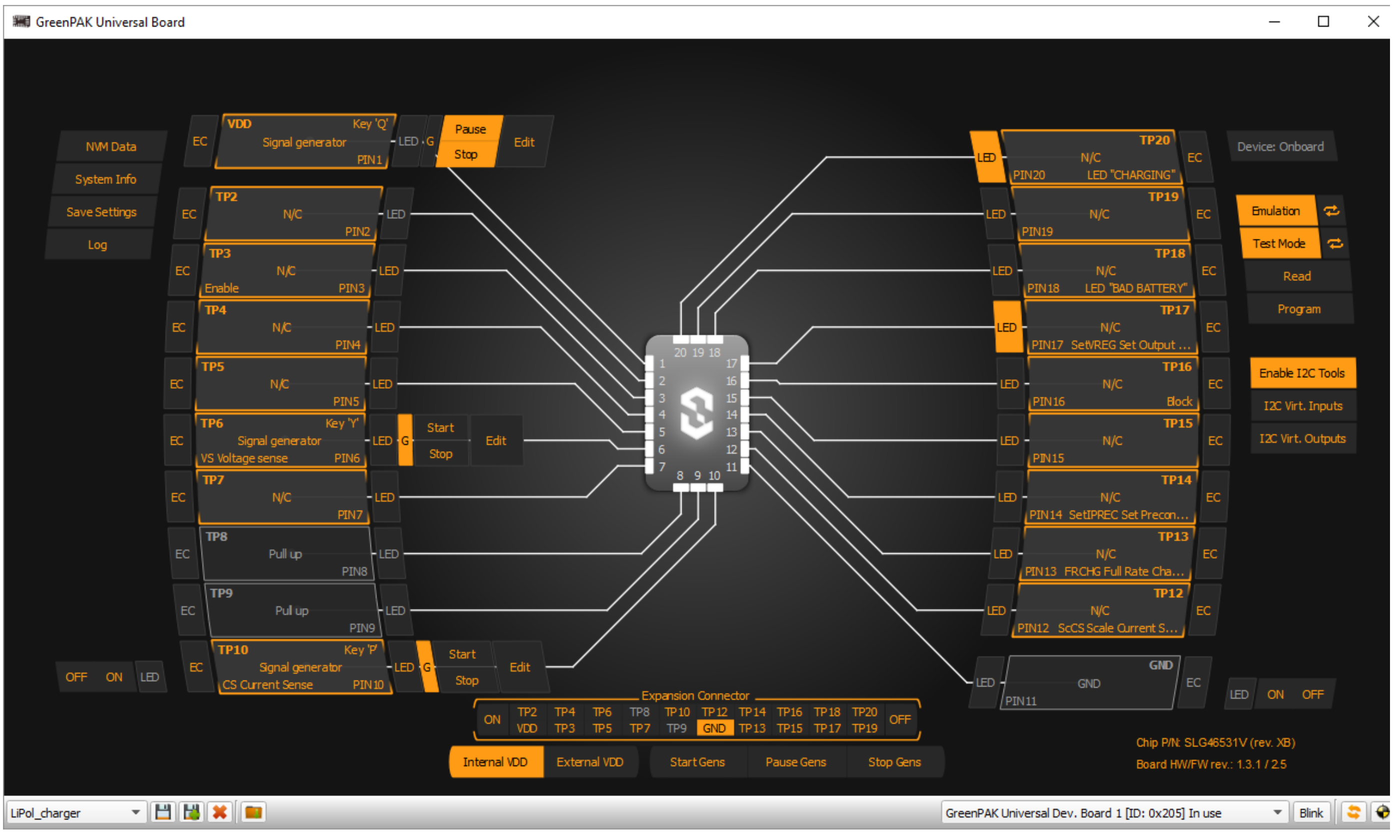

Figure 8. GreenPAK emulation window

Symbol	Parameter	Note	Min	Typ	Max	Unit
Vdd	Supply Voltage	5V ± 5%	4.75	5	5.25	V
	REGULATION					
Vreg	Output Voltage	4.2V ± 0.75%	4.17 4.22 4.32 4.35	4.2 4.25 4.35 4.38	4.23 4.28 4.38 4.41	V
ΔVbat/Vbat	Load regulation					
Ichg	Full rate charge current		2.3	2.5	2.7	A
	CONTROL					
Iprec	Preconditioning current	set to 10% set to 20% set to 40% disabled	8% 16% 32% ---	10% 20% 40% 100%	12% 24% 48% ---	Ichg
Vpth	Preconditioning Threshold		2.85	3	3.15	V
Vath	Recharge Threshold		3.8	3.95	4.1	V
Ieoc	End-of-charge Threshold	set to 5% set to 10% set to 15% set to 20%	4% 8% 12% 16%	5% 10% 15% 20%	6% 12% 18% 24%	Ichg
Ieop	End-of-topoff Threshold	set to 5% disabled	2.3%	2.5% 100%	2.7%	Ichg Ieoc
Vnobat	No battery threshold		4.45	4.6	4.75	V
	TIMING					
Tprec	Preconditioning Timeout	default @25°C	29	30	31	min
Tchg	Charging Timeout	default @25°C	4h50	5	5h12	hour
Ttop	Top-off Timeout	default @25°C	29	30	31	min
	Timing Error (all timers)	@25°C 0°C .. +85°C -40°C .. +85°C	-2.5% -11.61% -11.61%	default or set value	+3.89% +8.65% +9.95%	
	INTERFACE					
	I2C Specifications	See datasheet				
	Enable/Disable Input High	VIH	2.68		Vdd	V
	Enable/Disable Input Low	VIL	0		1.96	V
	Enable/Disable Input Leakage (Absolute Value)	ILKG	---	1	1000	nA

Table 4. Electrical Characteristics

I2C tools are used to check internal signal states like ASM outputs, analog comparator outputs, as well as the states of internal counters.

Control signals generated by GreenPAK are accessible on test pins of the GreenPAK Universal Development Board. Plots are shown in Fig. 9.

Test battery is a flat Li-Po battery 2400mAh 3.7V manufactured in China. Current mirror resistor is set to 250Ω, limiting the full rate charge current ICHG to 2.4Amps. End-of-charge current is set to 10%. ICHG.

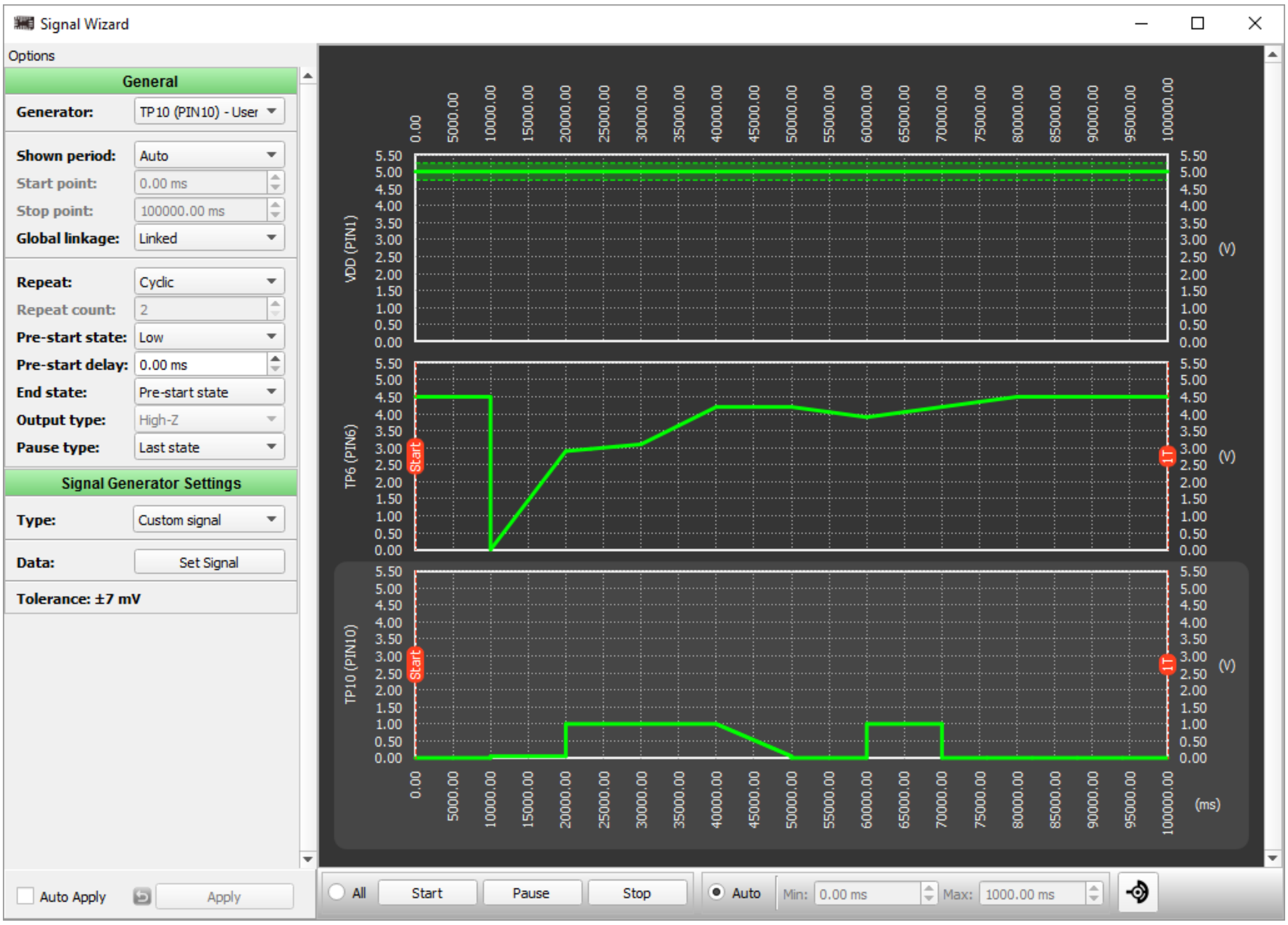

Figure 9. Example test plots

Final Testing

For the purpose of final testing, the power circuit is assembled on a breadboard and connected to the GreenPAK Universal Development Board using patch wires. External LEDs are not wired on the breadboard because LEDs are already available on the GreenPAK Development Board.

Timers are set to default values: preconditioning 30 min, charging 5 hours, top off 30 min. Before starting the test, the battery is discharged using a 2Ω resistor. This battery has built-in overdischarge protection and when the voltage falls below 2.5V, it switches off to a high impedance state.

Because of that, it was not possible to deplete this particular battery in order to demonstrate the preconditioning feature of the charger.

At the beginning of the test, battery voltage is below 3V and the charger is plugged into the power source. Connecting the battery to the charger triggers the transition from the *no battery* state to the *preconditioning* stage. As soon as the battery is connected to charger, battery voltage rises above 3.0V and the charger transitions to *charging* stage and the charging current is limited to full rate current ICHG. Preconditioning stage is too short to be seen in the plot of Fig. 10. During the charging process, a green LED indicates the charging stages. Battery voltage and charging current are measured and shown in Fig. 10. Constant current stage lasts about 15 minutes and constant voltage stage more than 2 hours. CC to CV timing ratio may be altered by adjusting the gain of voltage error amplifier.

The higher the gain the longer CC stage.

Once the charging current falls below end-of-charge threshold, the charger switches off the pass transistor and goes to maintenance mode. The charging current falls to zero and battery voltage falls slightly for a while, (normal chemistry processes of the battery), but stabilizes after a couple of minutes.

Conclusion

There are many specialized ICs designed for Li/Pol battery charging available on the market. They are typically mature, low power consumption, feature rich, high performance, programmable for extra flexibility, at a competitive price. The GreenPAK IC solution presented cannot compete as an exact replacement for one of those.

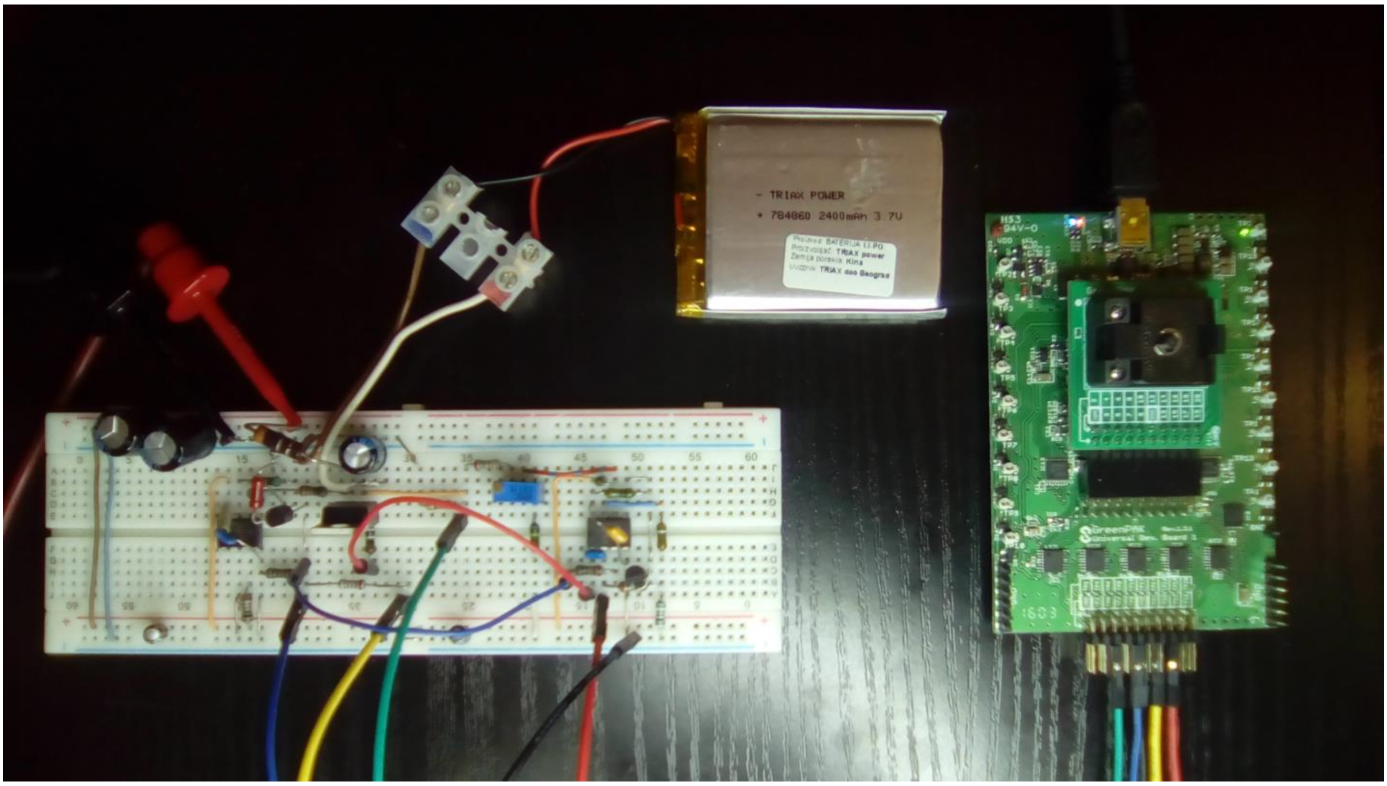

Figure 10. GreenPAK Universal Development Board

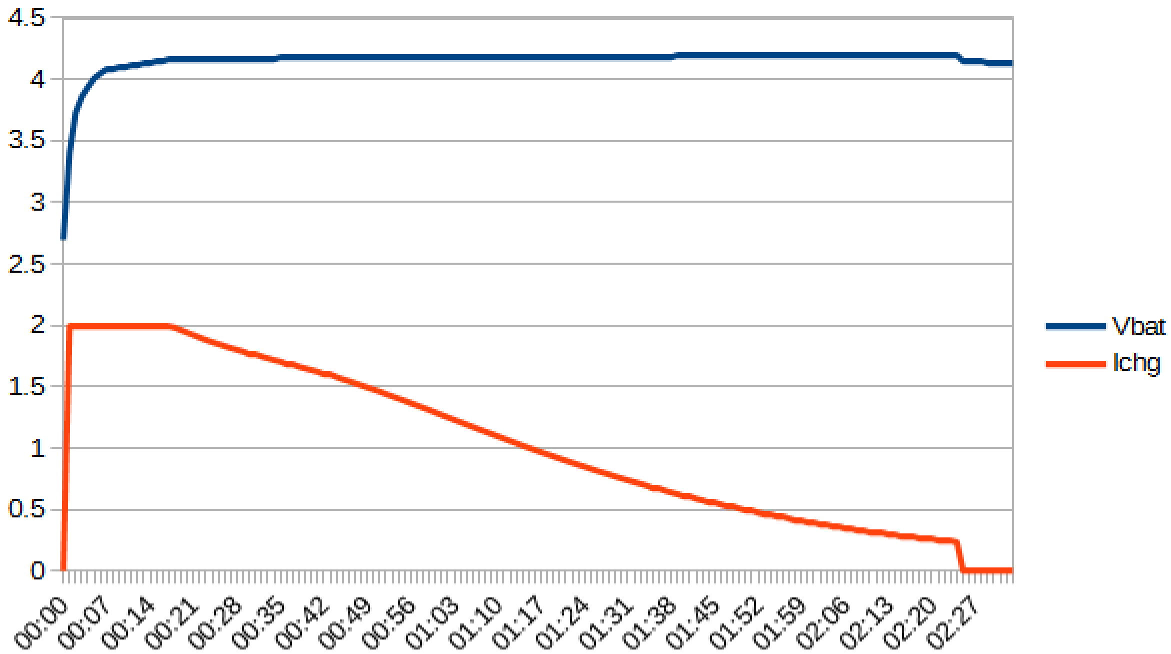

Figure 11. Measured Charging profile plot

However, the specialized ICs are still relatively limited and fixed. Applications where this GreenPAK IC based charger solution is favorable are those needing specific functions just not available in specialized ICs. There is surplus circuitry in GreenPAK that is available to implement functions related to battery charging process, or some other completely independent hardware functions that might be desired.

It was not intended for this application note to cover the charging of all configurations and capacities of Li Pol batteries. The purpose was to demonstrate the flexibility of the GreenPAK ecosystem and how it can offer the right solution to cover all of them with appropriate design.

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Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,
Koto-ku, Tokyo 135-0061, Japan
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