Precision Amplifiers for Battery Test Systems

Series Overview

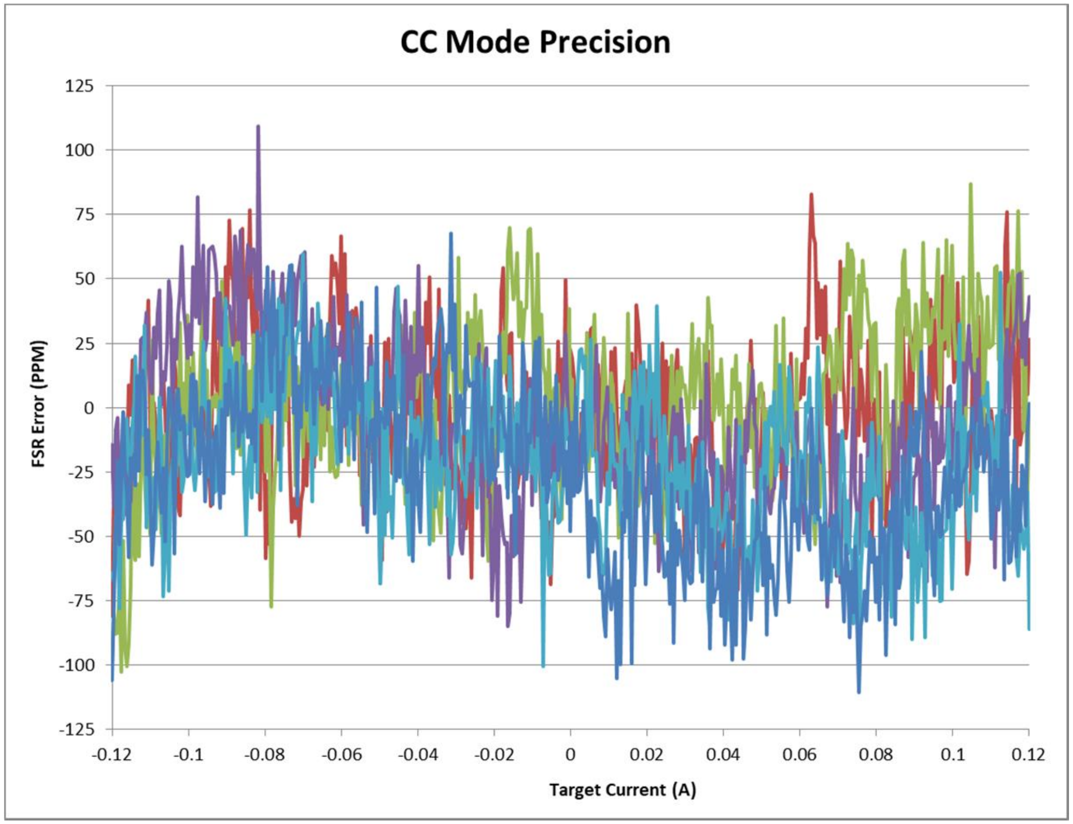
Precision Amplifiers

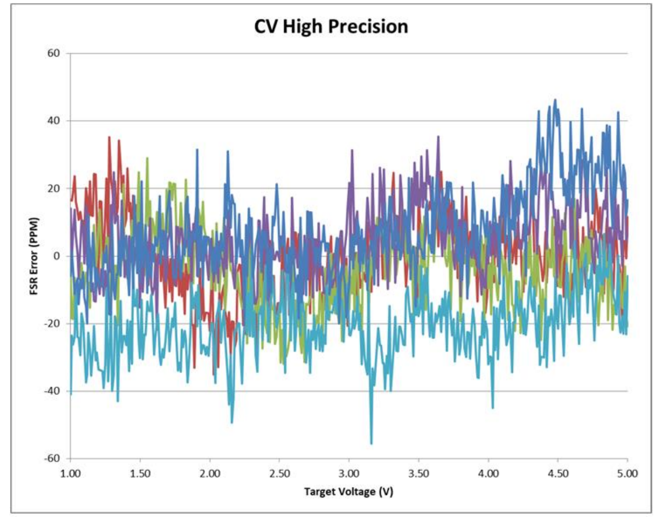
Series Agenda

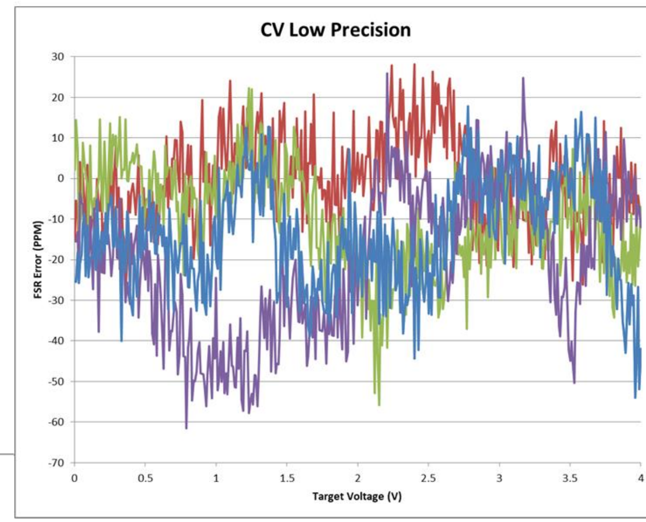
- **Series overview**
  - Testing theory
  - Charge/discharge cycles
- **Current sensing**
  - Important specs
- **Voltage sensing**
  - Important specs
- **Control loops**
  - CC control loop theory
  - CV control loop theory
  - Important specs

- **Drivers and buffers**
  - Driver (power amplifier)
  - Buffers (design dependent)
- **Simulation and results**
  - TINA-TI simulation
  - CC/CV accuracy results
  - Load regulation results

CC and CV Control Precision



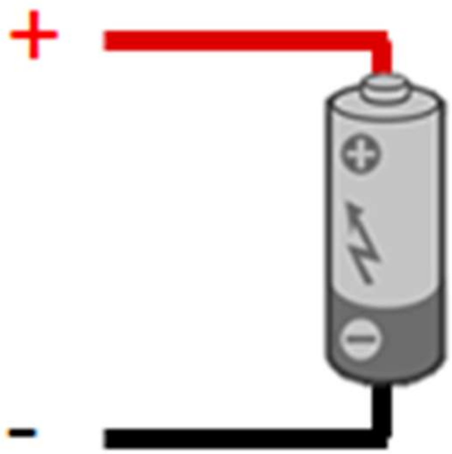




Run 1
Run 2
Run 3
Run 4
Run 5

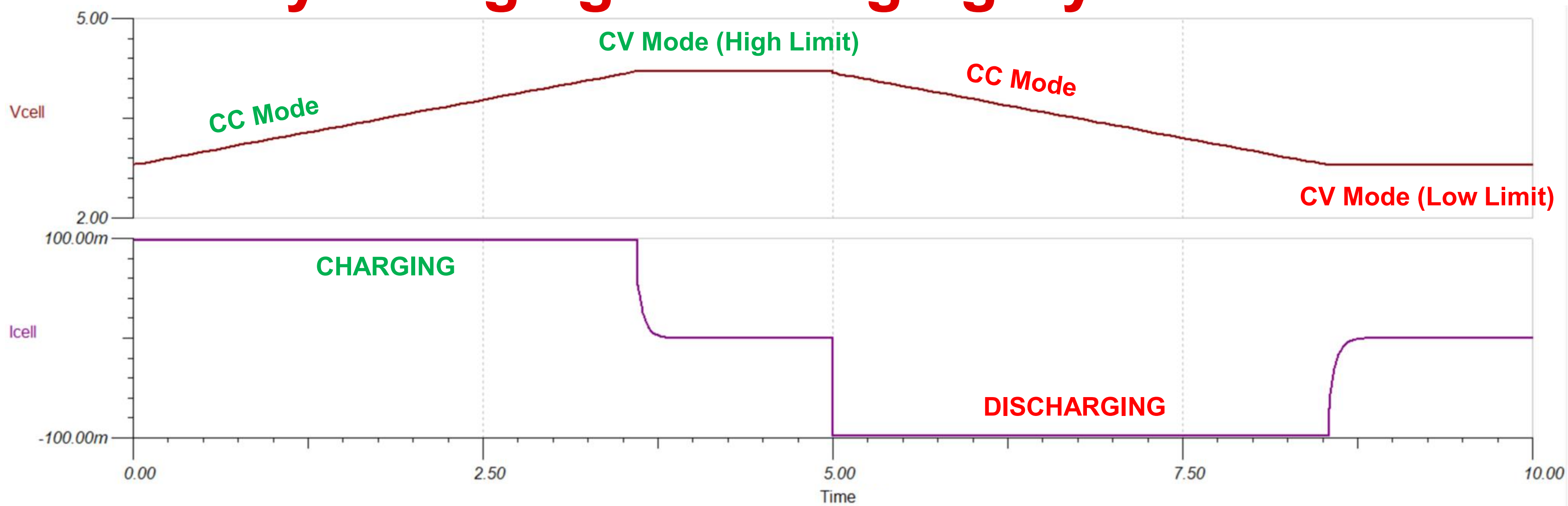
MENTS

Battery Test Theory Overview



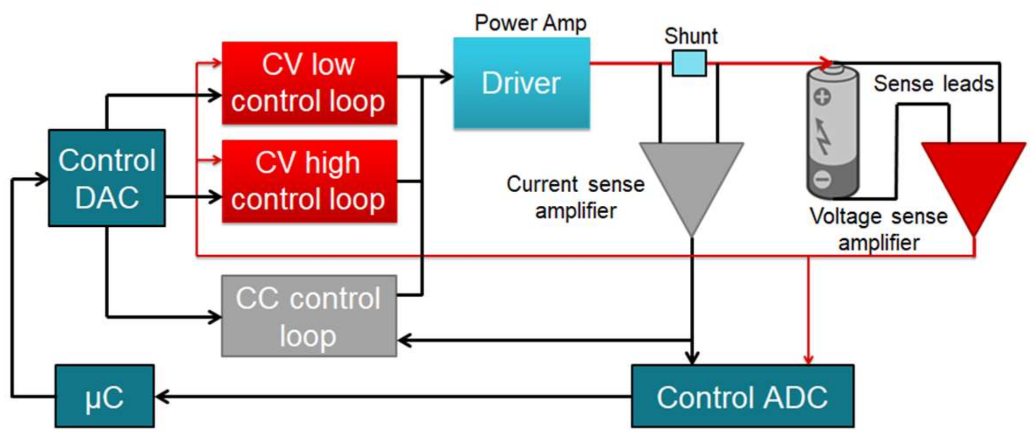
- For a single Li+/LiPo battery cell, there is a maximum battery voltage called the “regulation voltage” that represents the upper charging limit (usually ~4.2V, depending on the battery). There is also a minimum battery voltage called the “threshold voltage” that establishes the lower discharging limit (usually ~2.8V, any lower will damage the battery).
- For the purposes of this discussion, we will focus on charging/discharging only **one single-cell LiPo battery**
- Three main kinds of tests can be performed:
  - **Battery formation** – initialization charge/discharge cycle required for battery to store energy properly and to be graded
  - **Loop & Feature test** – repeated charge/discharge cycles to verify battery life and reliability are within tolerance
  - **Functional test** – test to make sure battery works properly before packaging

Li^+ Battery Charging/Discharging Cycles



- When the battery is charging/discharging at a fixed current, we call this **constant current (CC) mode**.
- When the battery voltage nears the regulation or threshold voltage, **constant voltage (CV)** mode takes over and current rolls off until the charging cycle is terminated

System Overview

Summary	System Block Diagram
In a battery test system… • The **battery cell test unit** houses the constant current and constant voltage control loops. • The **precision monitoring unit** collects battery voltage and current and provides feedback to the controller. The battery tester accuracy is impacted by: • INA used in **current sensing** • Precision amplifiers used as **buffers** • CC/CV **error amplifiers** A typical battery test circuit will utilize a buck/boost converter or a switching power supply & AC/DC power converter to drive charge/discharge of battery, but **power amplifiers** can be used for low-current and low-cost applications	

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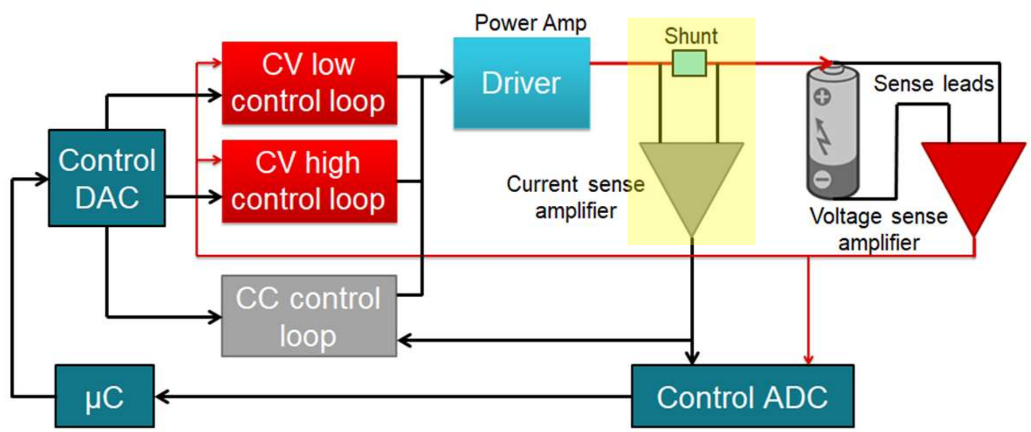
Precision Amplifiers for Battery Test Systems

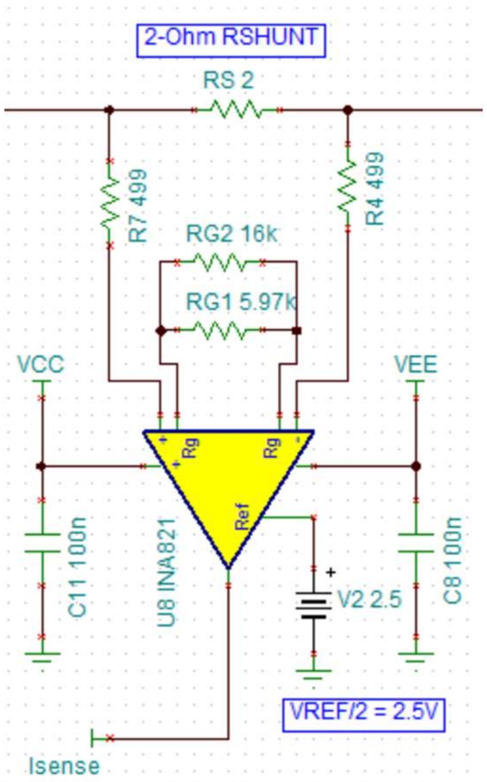
Current Sensing

Precision Amplifiers

Battery Current Sensing

Socket Function	System Block Diagram
Function – measure battery charge/discharge current via shunt resistor. • Typical shunt values are around 0.5Ω, smaller shunts require higher gain to make full use of dynamic range of amplifier • Accurate current measurement is crucial – used for calculating battery capacity, battery impedance, and even for battery health metrics Typically done with an **INA (Instrumentation Amplifier)** – benefits over integrated shunt current sense amplifiers include: • High input impedance • Noise performance • Gain optimization / configurability **Example product** – INA188	

Important Specs for Current Sensing



- Steady-state offsets may be accounted for the calibration. In this case, drift and linearity become the main error sources.
  - **Offset temperature drift** causes offset errors to worsen with increased temperature
  - **Bias current drift** increases input bias current IR drop across the current limiting resistors, worsening at higher temperatures
  - **Gain error drift** causes gain error to change with increased temperature
  - **Shunt resistance drifts** - high resistor tolerance and low drift are essential for robust accuracy

- **Linearity** – it is very important the amplifier has good gain linearity, in order to maintain a flat response across a wide range of load currents
- **Bandwidth** – want enough BW for the loop to update quickly, but not so much that high-frequency noise from nearby devices becomes a problem
- **Noise** – oversampling can reduce the effect of broadband noise, but 1/f noise cannot be averaged out

Precision Current Sensing Devices

Recommended Devices

	Highest BW Low Noise	Mid BW Lower Power	Lowest Drift
Specifications	**INA821**	**INA818/9**	**INA188**
Vs min/max (V)	4.5/36	4.5/36	4/36
Max Gain Nonlinearity (ppm, G=1)	10	10	8
GBW (MHz) (G=1)	4.7	2	0.6
Slew Rate (V/µs)	2.1	0.9	0.9
Vos max (µV)	35	35	55
Drift (Max) (µV/C)	0.4	0.4	0.2
CMRR (Max Gain) (Min) (dB)	140	140	118
Iq typ (mA)	0.6	0.35	1.6
1/f Input Voltage Noise (µVpp)	0.14	0.19	0.25
Ibias (Max) (nA)	0.5	0.5	2.5
Gain Error (% Max)	0.15	0.15	0.5
Gain Drift (ppm/°C)	35	35	50
Added Features	± 40 OVP	± 60 OVP	RFI-Filtered
Technologies	Super-beta	Super-beta	Zero-drift

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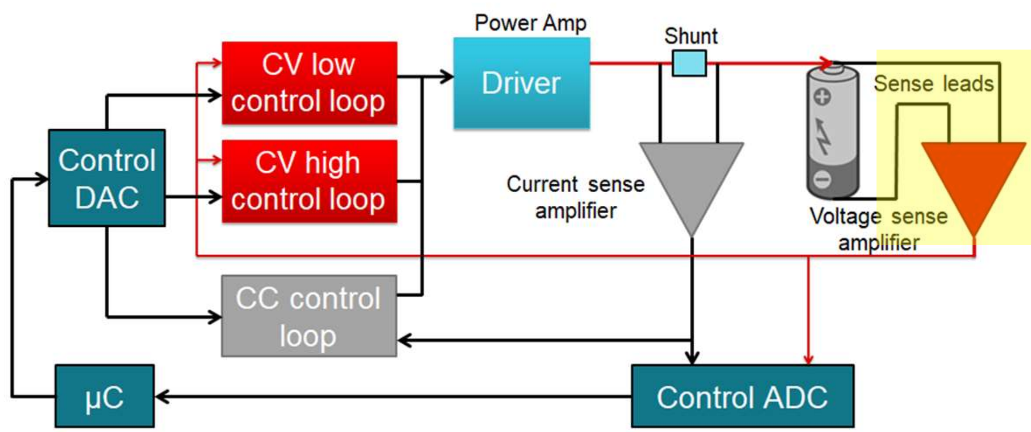
Precision Amplifiers for Battery Test Systems

Voltage Sensing

Precision Amplifiers

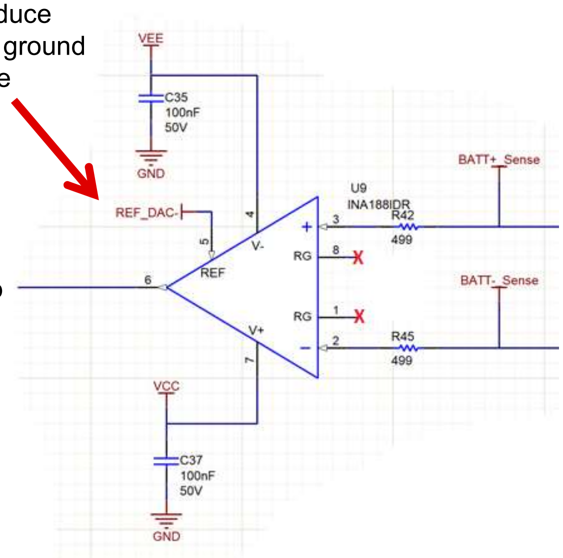
Battery Voltage Sensing

Socket Function	System Block Diagram
Function – Precisely monitor the voltage across the battery terminals • Accurate voltage measurement ensures the tester does not over-charge or over-discharge the battery (exceed the regulation voltage or go below the threshold voltage) • Op amp selection depends on system accuracy requirements **Example product** – OPA188, INA188	

4-Lead Wire Battery Voltage Sense

- Sense leads to the terminals are monitored for **battery voltage measurement**, instead of the connections to the driver output
- This **4-wire remote sensing** reduces voltage offset error because the charge/discharge current does not pass through the sense leads, which only look into the high-impedance inputs of the amplifier. Therefore the only I*R drop across the current limiting resistors is due to the input bias current

Referenced to DAC ground to reduce possibility of ground offset/bounce

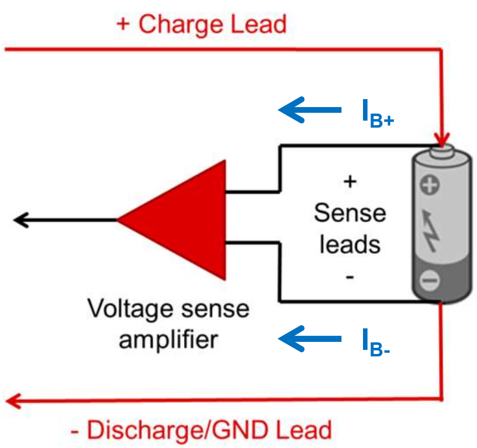


To CV loop

From battery sense lead +

From battery sense lead -

Important Specs for Battery Voltage Sense



- **Offset voltage** results in incorrect measurement of battery terminals
- **Offset temperature drift** causes offset errors to worsen as temperature rises
- **CMRR** determines offset error due to common mode voltage
- **Input bias current** causes an IR drop across the current limiting resistors (R_{LIM}), again worsening at higher temperatures

- **Input offset current** ($I_{B+} - I_{B-}$) results in a different IR drop on the +/- inputs, resulting in incorrect differential measurement across terminals.
- If voltage sense amplifier bias current is high enough relative to charge/discharge current, some current intended for battery will be redirected, reducing current measurement accuracy

$$V_{ERR\_RTI} = V_{OS\_MAX} + \frac{dV_{OS}}{dT_{max}} * \Delta T + \frac{V_{BAT}}{CMRR} + (I_{B+} * R_{LIM+} - I_{B-} * R_{LIM-}) + \cdots$$

Precision Voltage Sensing Devices

Recommended Devices

	Cost Optimized	Cost Optimized / Lowest Power	Lowest Power	Lowest Drift	Widest Bandwidth
Specifications	**TLV07**	**TLV2186**	**OPAx188**	**OPAx182**	**OPAx189**
Vs min/max (V)	2.7 / 36	4.5 / 24	4 / 36	4.5 / 36	4.5 / 36
CMRR typ (dB)	120	134	146	168	168
GBW (MHz)	1	0.75	2	5	14
Slew Rate (V/µs)	0.4	0.35	0.8	10	20
Vos max @ 25C (mV)	0.1	0.25	0.025	0.004	0.005
Drift typ (µV/C)	0.9	0.1	0.03	0.003	0.007
Rail-to-Rail	Out	In, Out	In to V-, Out	Out	In to V-, Out
Iq typ (mA)	0.95	0.09	0.425	0.85	1.3
Vn (nV/√Hz)	19	38	8.8	5.7	5.2
IBias typ (pA)	40	100	160	50	70
Operating Temperature (°C)	-40 to 125	-40 to 125	-40 to 125	-40 to 125	-40 to 125
Technology	-	Zero-drift	Zero-drift	Zero-drift	Zero-drift

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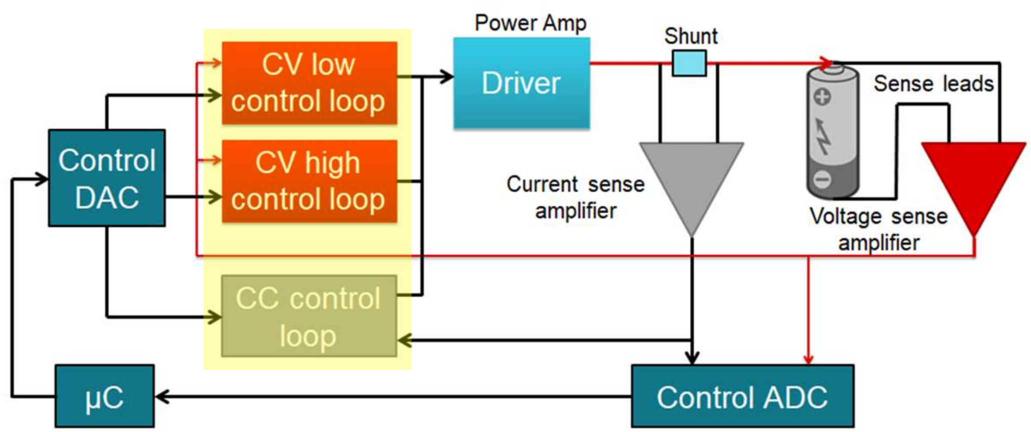
Precision Amplifiers for Battery Test Systems

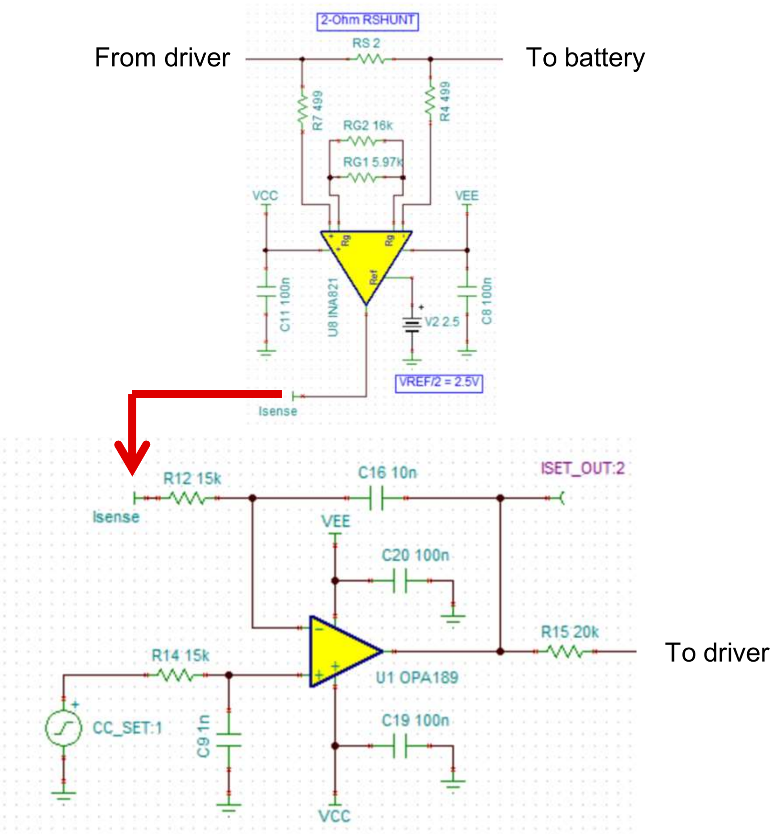
Control Loops

Precision Amplifiers

CC/CV Control Loops

Socket Function	System Block Diagram
Function: • The CC/CV control loops need high-precision error amplifiers to calibrate the target signal. • Due to the high current of this application, changes in temperature due to dissipated heat will have an effect on the performance of this board. The input offset voltage drift is a **key parameter** to consider when choosing the amplifier • Mux-friendly devices are best, as the amplifiers' inputs often see a significant differential voltage **Example product** – OPA189	

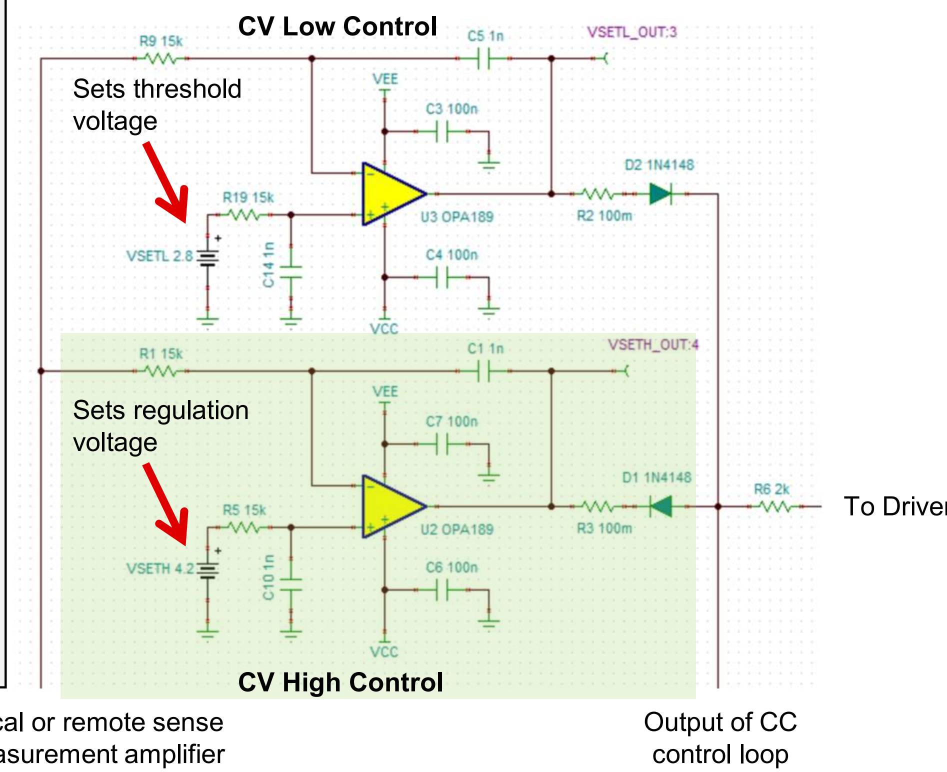
Current Control Loop Example



- Output of current sense amp feeds back to current error amplifier, which calibrates the ISET_OUT output relative to the specified CC_SET level from the DAC
- For CC_SET < $V_{REF/2}$, the battery will discharge down to the threshold voltage.
- For CC_SET > $V_{REF/2}$, the battery will charge up to the regulation voltage. The delta between CC_SET and $V_{REF/2}$ determines the drive current for charge or discharge.
- In example shown, CC_SET ranges from 0V min to 5V max, and $V_{REF/2}$ = 2.5V

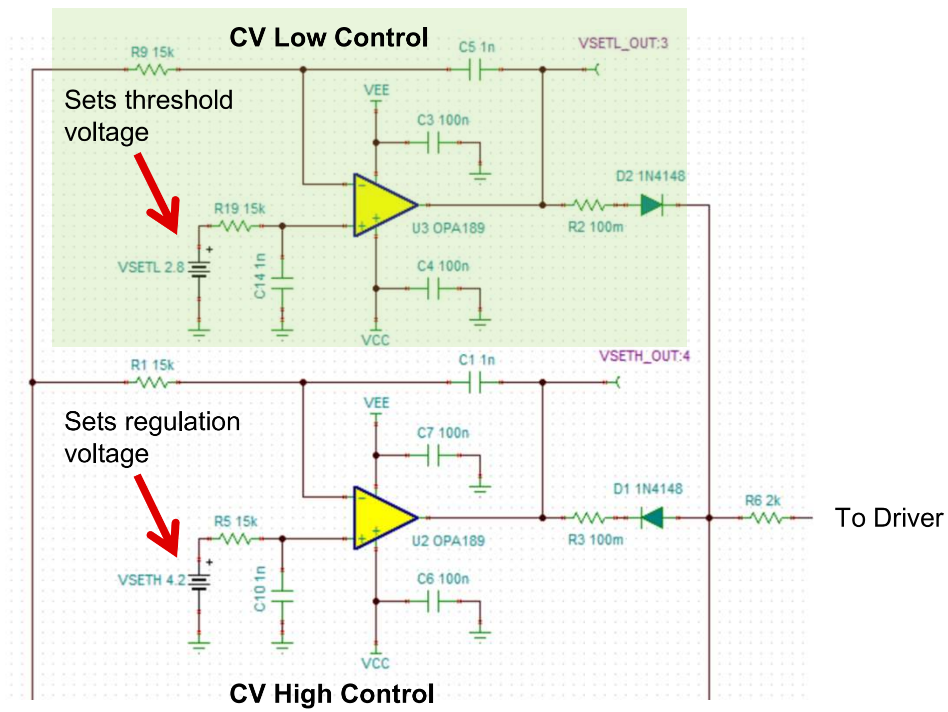
$V_{battery}$ Upper Limit Detection in Control Loop

- To support both charge and discharge, both a **CV High** and **CV Low control** loop are needed.
- During charging, when battery voltage nears regulation voltage, **CV High “turns on”** to counter the CC loop.
- VSETH_OUT falls to a diode drop below the desired battery voltage.
- VSETL_OUT is low so D2 is off, and CV High overpowers the CC control loop amplifier to set the driver voltage



$V_{battery}$ Lower Limit Detection in Control Loop

- When battery voltage nears the threshold voltage during discharge, **CV Low** activates to stop further discharge and hold battery voltage at threshold.
- VSETL_OUT rises to a diode drop above the desired battery voltage.
- VSETH_OUT is railed to VCC so D1 is off, and CV Low overpowers the CC control loop to set the driver voltage



FB from local or remote sense battery measurement amplifier

Output of CC control loop

Precision Control Loop Devices

Recommended Devices

	Lowest system cost		Mux-Friendly: e-Trim™ Low Cost	Mux-Friendly: e-Trim™ Higher Performance	Mux-Friendly: Zero-Drift Widest Bandwidth
Specifications	**TLV07**	**TLV2186**	**OPAx197**	**OPAx192**	**OPAx189**
Vs min (V)	2.7	4.5	4.5	4.5	4.5
Vs max (V)	36	24	36	36	36
GBW (MHz)	1	0.75	10	10	14
Slew Rate (V/µs)	0.4	0.35	20	20	20
Vos max @ 25C (mV)	0.1	0.25	0.1	0.025	0.005
Drift typ (µV/C)	0.9	0.1	0.5	0.15	0.007
Rail-to-Rail	Out	In, Out	In, Out	In, Out	In to V-, Out
Iq typ (mA)	0.95	0.09	1	1	1.3
Vn (nV/√Hz)	19	38	5.5	5.5	5.2
IBias (Typ) (pA)	40	100	5	5	70
Operating Temperature (°C)	-40 to 125	-40 to 125	-40 to 125	-40 to 125	-40 to 125

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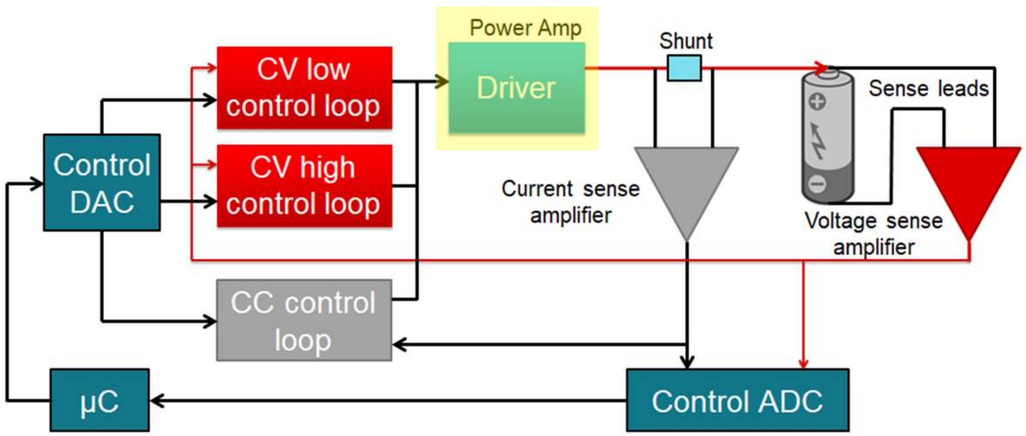
Precision Amplifiers for Battery Test Systems

Drivers and Buffers

Precision Amplifiers

Power Amp Driver (Optional - Design Dependent)

Socket Function	System Block Diagram
Function – The driver should be chosen based on the current needs of the application and the supply voltages available. The supplies are often set much higher than the maximum battery voltage – this added headroom may be necessary to force a given current value • Consider the thermal dissipation of the device when designing a high-current BTS system. Designing beyond 1A can be quite difficult due to self-heating • Consider selecting a device with built-in current limiting features **Example product** – ALM2402F	

Precision Power Amp Devices

Recommended Devices

	Smallest Package Lowest system cost		Highest Output Current Drive	
Specifications	**TLV4110/1**	**TLV4112/3**	**ALM2402F-Q1**	**OPA564**
Num Channels	1	1	2	1
Vs min (V)	2.5	2.5	4.5	7
Vs max (V)	6	6	16	24
Output Current Drive (mA)	320	320	400	1500
Operating Temperature (°C)	-40 to 125	-40 to 125	-40 to 125	-40 to 85
Additional Features	Shutdown Pin	Shutdown Pin	Protection Features	Protection Features

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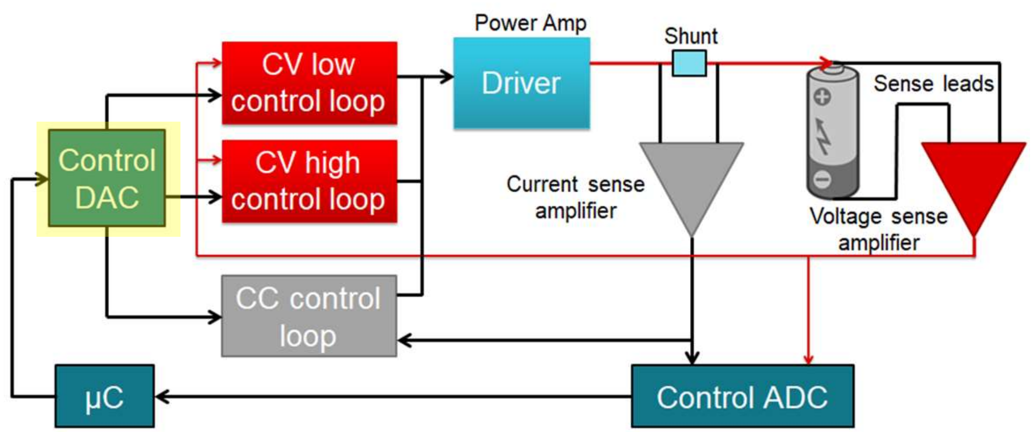
DAC Op Amp Buffer (Optional - Design Dependent)

Socket Function	System Block Diagram
Function – Precision amps may be used to **buffer/gain up the DAC** control outputs to change the output range of the DAC and set the reference voltage • This is design dependent – if DAC outputs look into **high impedance inputs** of control amplifiers, buffers not likely necessary. However, some DACs such as **current output DACs** may require buffering • The $V_{REF/2}$ current sense reference voltage may be achieved locally by using a precision device to buffer a high-tolerance voltage divider between the DAC supplies **Example product** – OPA188	

Precision Buffer Devices

Recommended Devices

	CMOS, e-Trim™		Bipolar, Super-beta		Zero-drift
	Low Cost	Higher Performance	Lowest power	Lowest noise, wide BW	Lowest offset & drift
Specifications	**OPAx197**	**OPAx192**	**OPAx205**	**OPAx210**	**OPAx189**
Vs min (V)	4.5	4.5	4.5	4.5	4.5
Vs max (V)	36	36	36	36	36
GBW (MHz)	10	10	3.6	18	14
Slew Rate (V/µs)	20	20	4	6.4	20
Vos max @ 25C (mV)	0.1	0.025	0.025	0.035	0.005
Drift typ (µV/C)	0.5	0.15	0.1	0.5	0.007
Rail-to-Rail	In, Out	In, Out	Out	Out	In to V-, Out
Iq typ (mA)	1	1	0.22	2.2	1.3
Vn (nV/√Hz)	5.5	5.5	7.2	2.2	5.2
IBias (Typ) (pA)	5	5	200	300	70
Operating Temperature (°C)	-40 to 125	-40 to 125	-40 to 125	-40 to 125	-40 to 125

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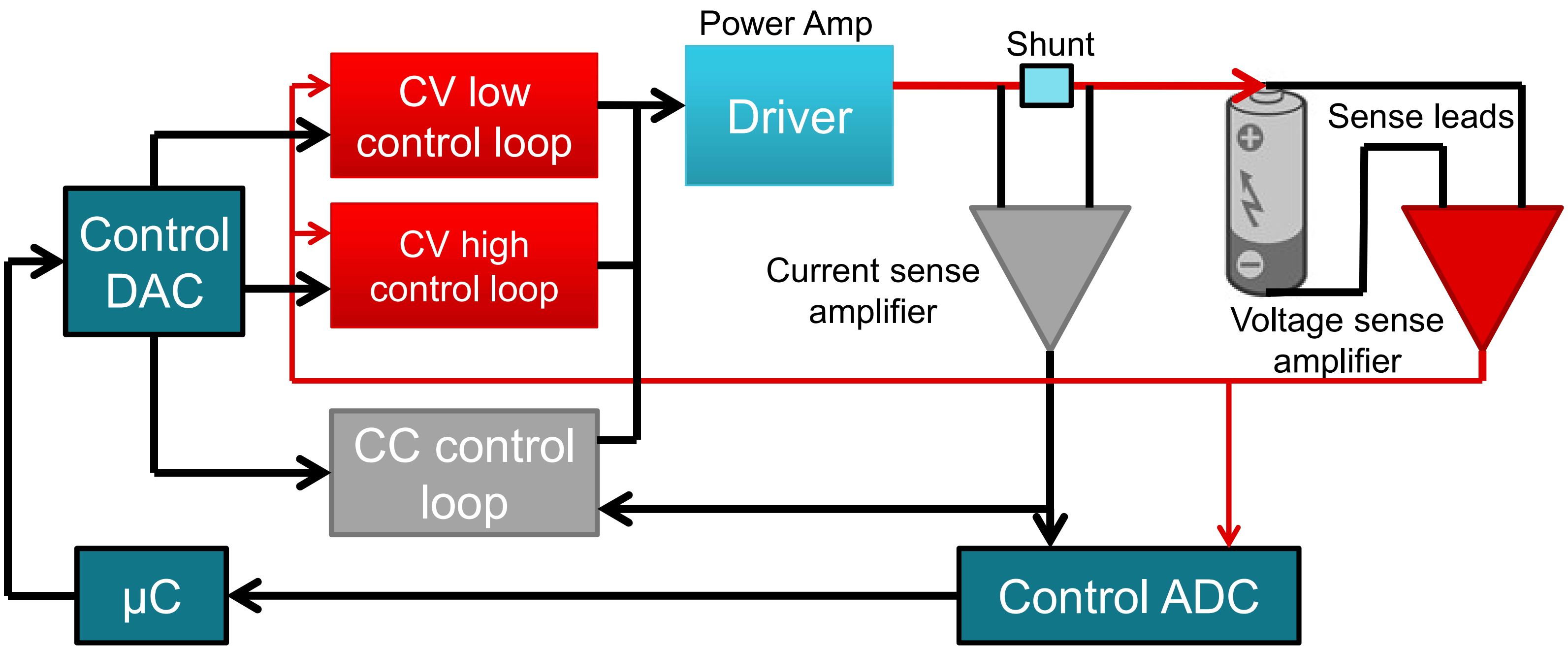
Precision Amplifiers for Battery Test Systems

Simulation and Results

Precision Amplifiers

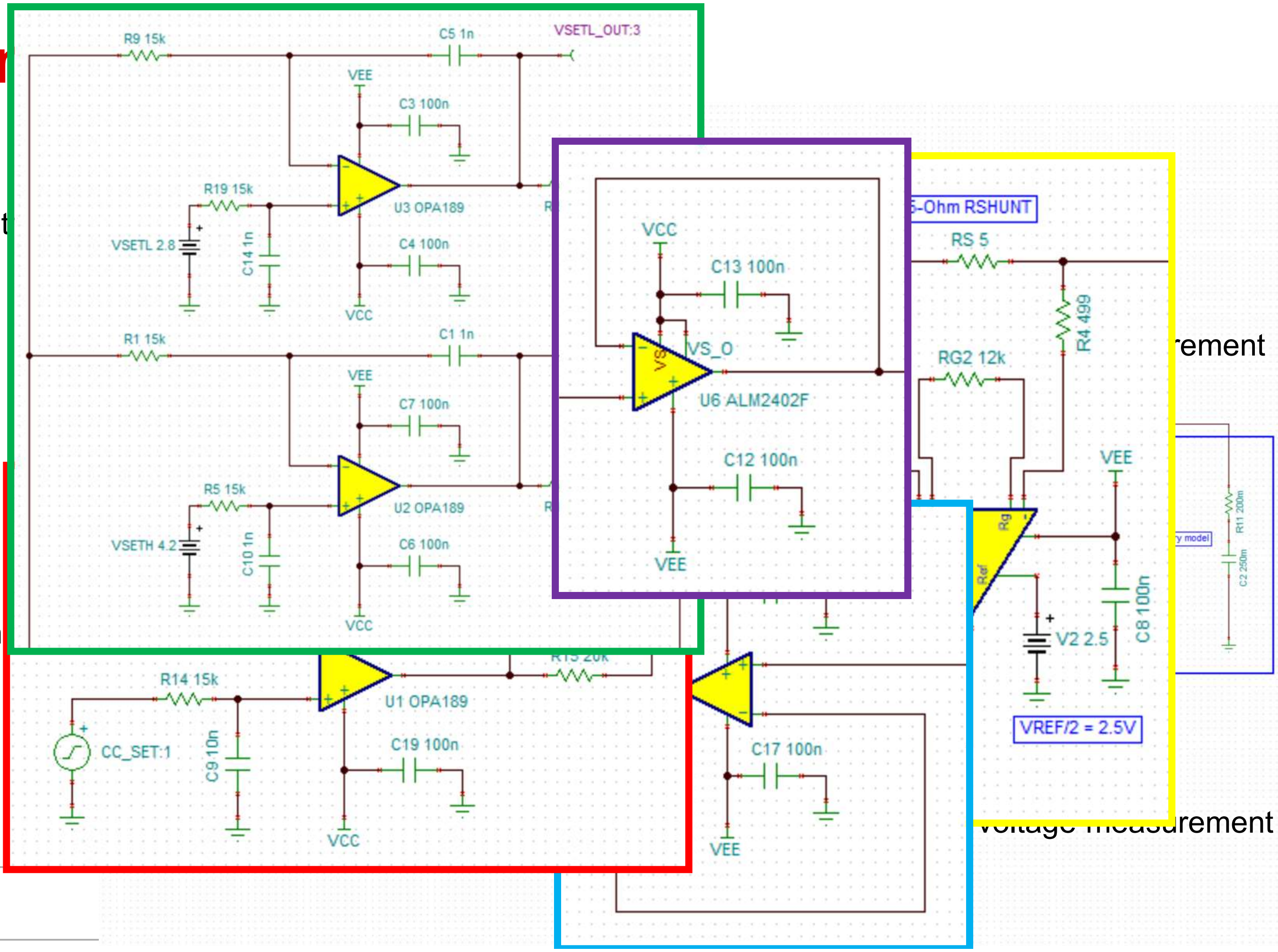
Power Amp Charging/Discharging System Overview



Exa

CV cont

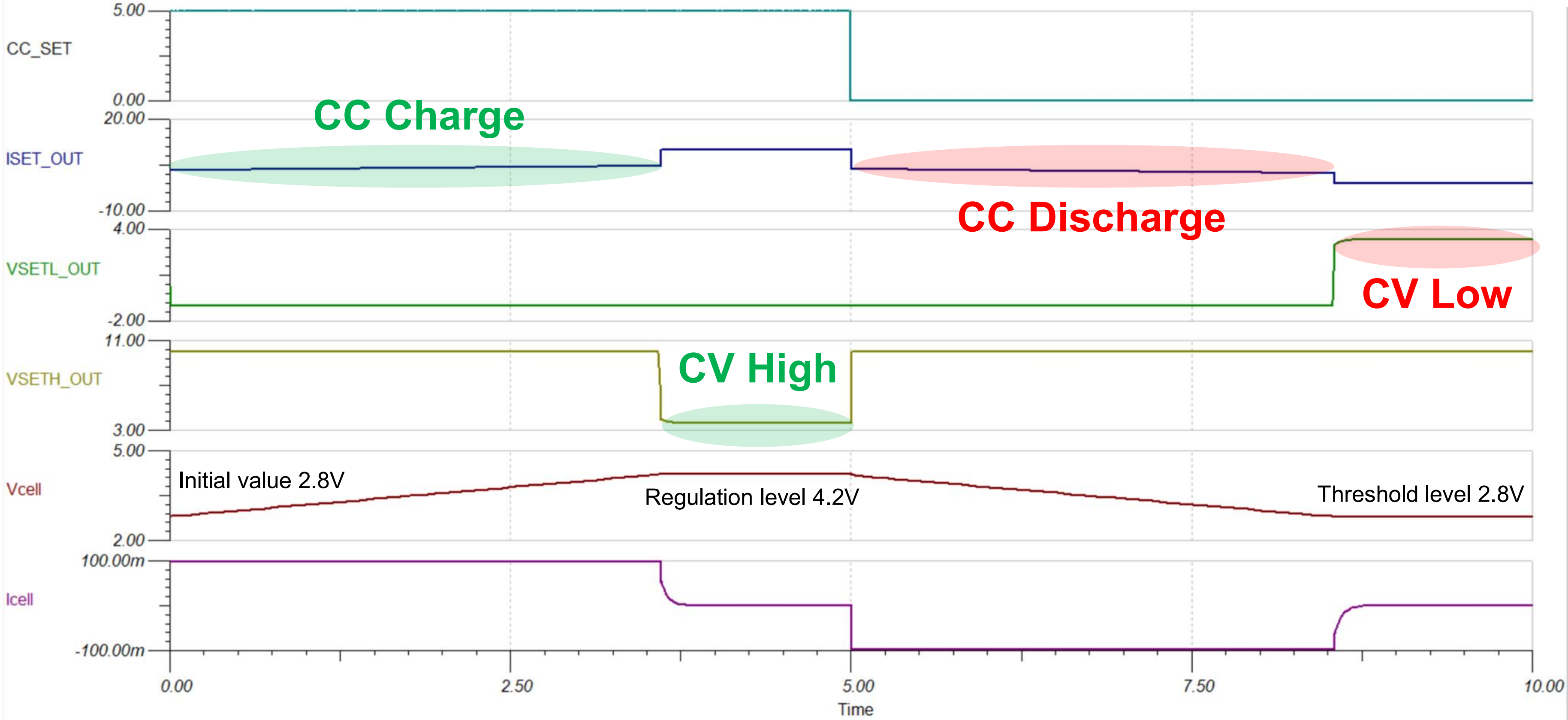
CC con



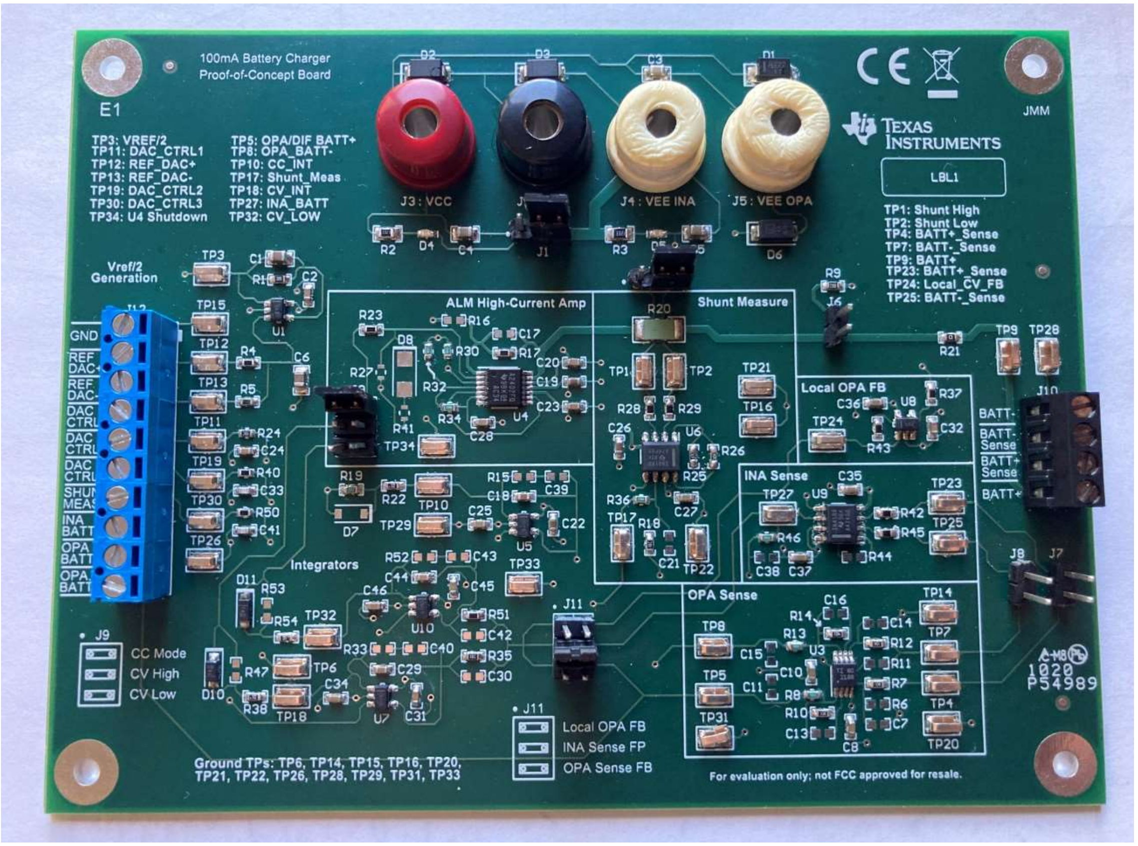
rement

voltage measurement

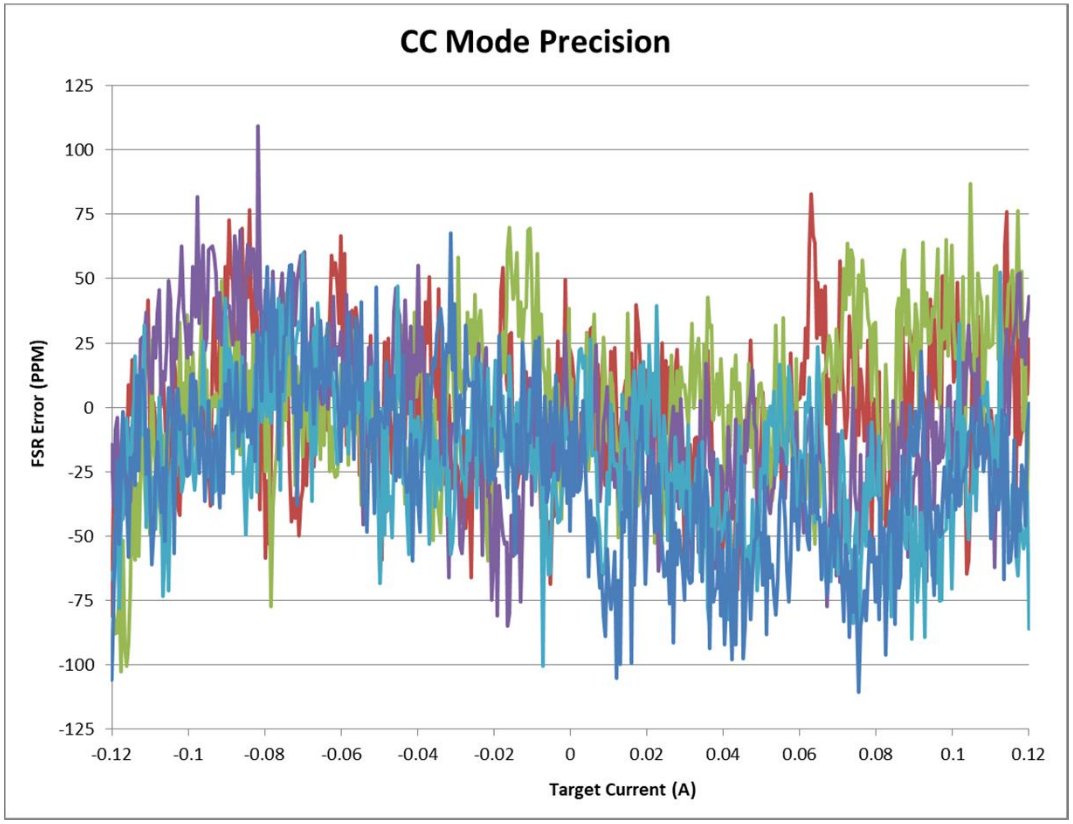
Example Simulation

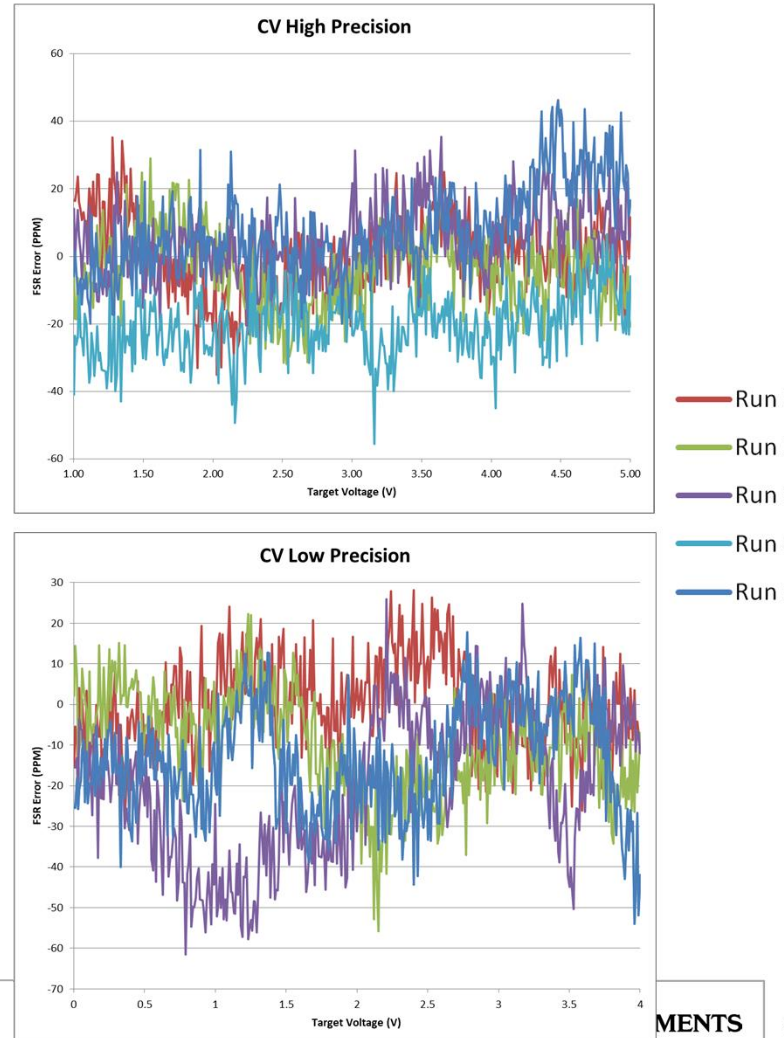


Hardware Solution

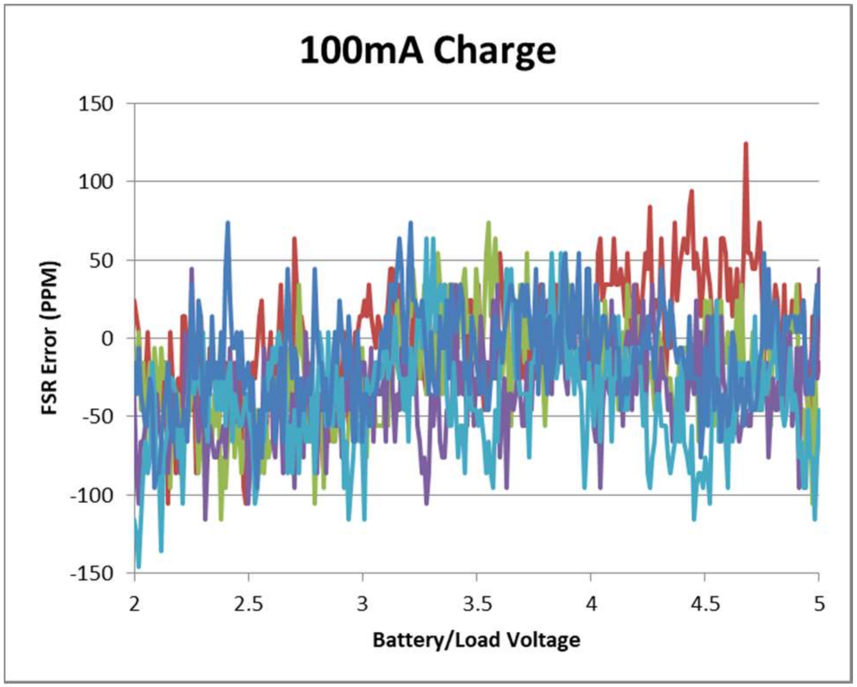


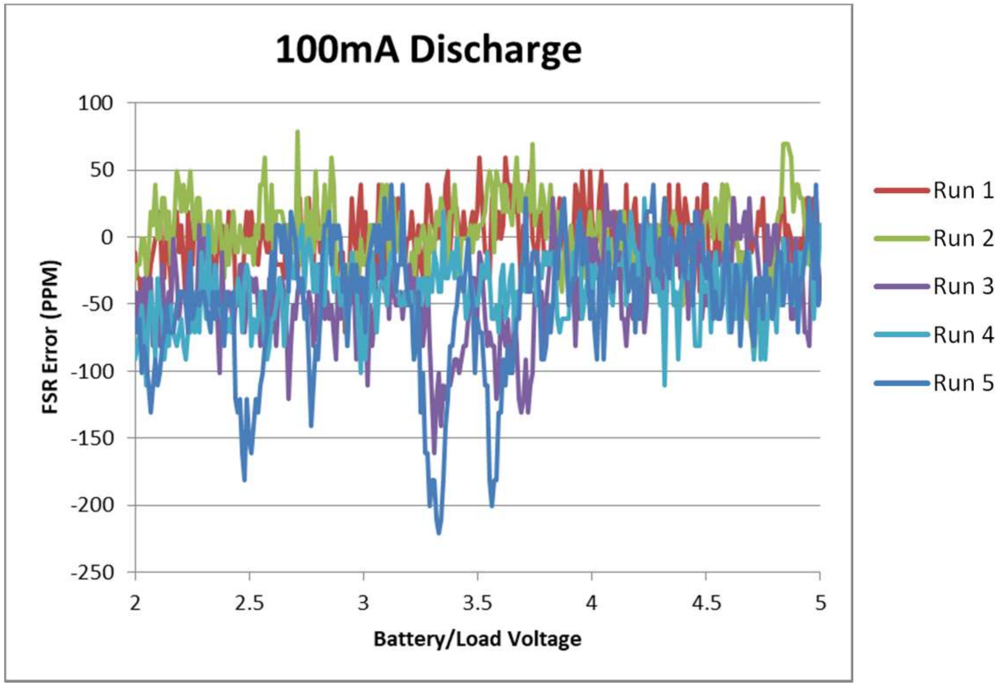
CC and CV Control Precision





CC Precision vs Battery Voltage





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