Design considerations for high cell count applications

Steven Schnier

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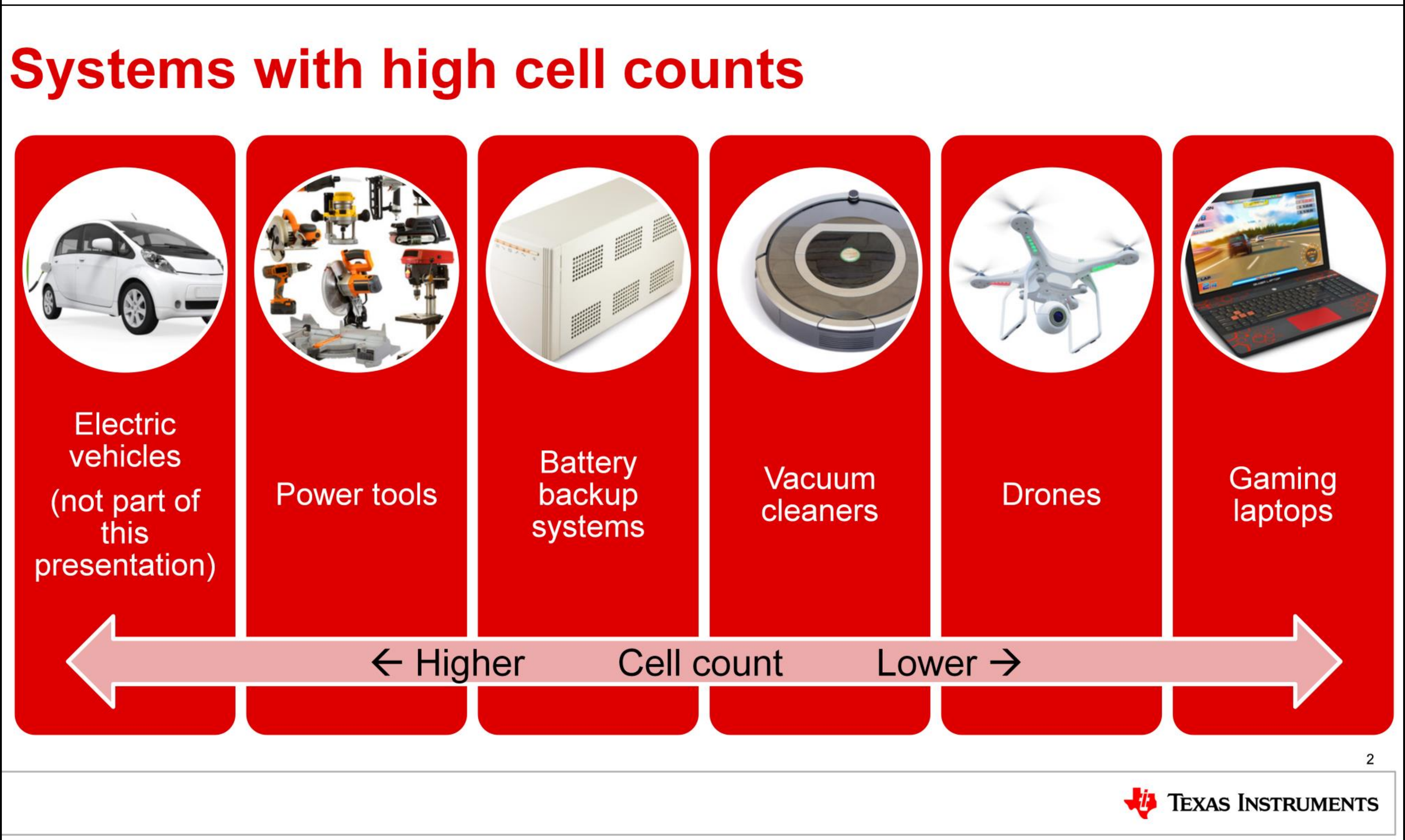
TEXAS INSTRUMENTS

There are many design considerations for high cell count batteries when it comes to gauging and protection. Today I will go through some of the most common challenges presented by these systems.



You are most likely familiar with single cell battery applications like cell phones, mp3 players, wearables, and the like. There are many applications which need more power, and therefore use a combination of cells to create higher voltage and higher current battery packs. Some of the most common are shown here. One of the highest cell count applications is electric vehicles, but since this topic requires considerations of automotive quality and other unique application considerations, I am not covering it here. Power tools are typically less 13S or less, which means there are 13 cells in series for a typical voltage of 48V or less. Battery back up systems are typically provide an adjustable 12V output, and the battery configuration varies. Vacuum cleaning robots and battery powered stick vacuums are typcially between 4S and 7S, whereas drones can also have packs configured in that range. Most notebooks are 2S to 4S, but now some gaming notebooks are 5S, and may go higher in the future. The cell chemistries in each application differs, but each needs gauging and protection.

Battery technology comparison

Specifications	Lead-Acid	NiCd	NiMH	Li-Ion: Cobalt	Li-Ion: Manganese	Li-Ion: Phosphate
Specific energy density (Wh/kg)	30 – 50	45 – 80	60 – 120	150 – 190	100 – 135	90 – 120
Internal resistance (mΩ/V)	<8.3	17 – 33	33 – 50	21 – 42	6.6 – 20	7.6 – 15.0
Cycle life (80% discharge)	200 – 300	1,000	300 – 500	500 – 1,000	500 – 1,000	1,000 – 2,000
Fast-charge time (hrs.)	8 – 16	1 typical	2 – 4	2 – 4	1 or less	1 or less
Overcharge tolerance	High	Moderate	Low	Low	Low	Low
Self-discharge/month (room temp.)	5 – 15%	20%	30%	<5%	<5%	<5%
Cell voltage	2.0	1.2	1.2	3.6	3.8	3.3
Charge cutoff voltage (V/cell)	2.40 (2.25 float)	Full charge indicated by voltage signature	Full charge indicated by voltage signature	4.2	4.2	3.6
Discharge cutoff volts (V/cell, 1C*)	1.75	1	1	2.5 – 3.0	2.5 – 3.0	2.8
Peak load current**	5C	20C	5C	> 3C	> 30C	> 30C
Peak load current* (best result)	0.2C	1C	0.5C	<1C	< 10C	< 10C
Charge temperature	-20 – 50°C	0 – 45°C	0 – 45°C	0 – 45°C	0 – 45°C	0 – 45°C
Discharge temperature	-20 – 50°C	-20 – 65°C	-20 – 65°C	-20 – 60°C	-20 – 60°C	-20 – 60°C
Maintenance requirement	3 – 6 months (equalization)	30 – 60 days (discharge)	60 – 90 days (discharge)	None	None	None
Safety requirements	Thermally stable	Thermally stable, fuses common		Protection circuit mandatory		
Time durability				>10 years	>10 years	>10 years
In use since	1881	1950	1990	1991	1996	1999
Toxicity	High	High	Low	Low	Low	Low

Source: batteryuniversity.com. The table values are generic, specific batteries may differ.
*"C" refers to battery capacity, and this unit is used when specifying charge or discharge rates. For example: 0.5C for a 100 Ah battery = 50 A.
**Peak load current = maximum possible momentary discharge current, which could permanently damage a battery.

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Many high cell count applications choose Li-Ion batteries, which is the most common battery chemistry for a variety of applications, but other chemistries are still used depending on the application. Due to their many benefits, their popularity has helped drive down the cost of Li-Ion cells significantly since they were introduced in 1991. Li-ion batteries have the hightest cycle life other than NiCd, but have less self-discharge and higher energy density. This makes them ideal for applications that need a lot of power, but need the batteries to be small and light. This combination of affordable, high density, quick-charging rechargeable batteries has enabled Li-Ion batteries to be used in many applications that have formerly been corded or have used small gasoline powered engines. However, high cell count Li-ion battery packs require more care in the charging and protection circuitry, as they are not tolerant of over-charging, can not be trickle charged like Lead-Acid, and require protection circuitry.

Safety standards for consideration

Safety certification standards

- UL 2595 – General Requirements for Battery-Powered Appliances
- UL 1642 – Standard for Lithium Batteries

International safety standards

- IEC 62133 – Safety Requirements for Portable Sealed Secondary Cells, and for Batteries Made from Them, for Use in Portable Applications
- IEC 61508 – Functional Safety

United Nations Classifications on the Transport of Dangerous Goods

- UN 3171 – Battery-Powered Vehicle or Battery-Powered Equipment
  - Applies to scooters, eBikes, and hoverboards too!
- UN 3480 – Lithium Ion Batteries
- UN 3481 – Lithium Ion Batteries Packed with Equipment Including Lithium Ion Polymer Batteries

Packing instructions

- PI 965 – 970 – Packing Instructions for Lithium-Based Battery Products

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Depending on the type of product being produced, it may fall under a variety of safety standards and certifications. One of the most broadly applicable is the Underwriter Laboratories, or UL, 2595 which is the general requirement for battery powered appliances. If your product has an integrated or detachable battery up to 75V, this standard will likely apply to you. This standard only covers the battery safety, and not all safety concerns, so other standards may apply. Also, this standard doesn’t apply to the battery charger, but only the battery and it’s protection requirements to address the risk of fire or explosion only, and not toxicity which is inherent to the battery chemistry. The UL1642 standard addresses many of the functional tests required for the cells themselves, which are usually addressed by the cell maker, not the system maker.

Since many products are developed for use all over the world, it is necessary to consider international standards. Many standards overlap each other, and this is the case with many International electrotechnical Commission, or IEC, standards such as IEC62133, which overlaps UL1642. Many countries particpate in the Certification Body scheme, where participating laboratories are able to give manufactures a simplified way of obtaining multiple national safety certifications for their products. Right now, there are around 50 countries that accept the CE and CB marking scheme.

After you’ve considered the safety standards that your cell supplier has to meet, and the safety standards that your system has to meet, you also need to consider the special requirements for shipping your product that integrates a high cell count battery. Several United Nations classifications may apply, such as UN3171 which applies to battery-powered vehicles and equipment, which include hoverboards, e-bikes, scooters, and much more. The International Air Transport Association, IATA, issues battery guidance for safe transport by air, including guidance on the amount of charge that can be in the cells. Packing Instructions, PI, 965 through 970 apply to shipping batteries safely depending on the type of battery and whether they are shipped loose or in the end equipment.

Example of UL2595 compliance with BQ40z80

- The standard requires protection against the following:

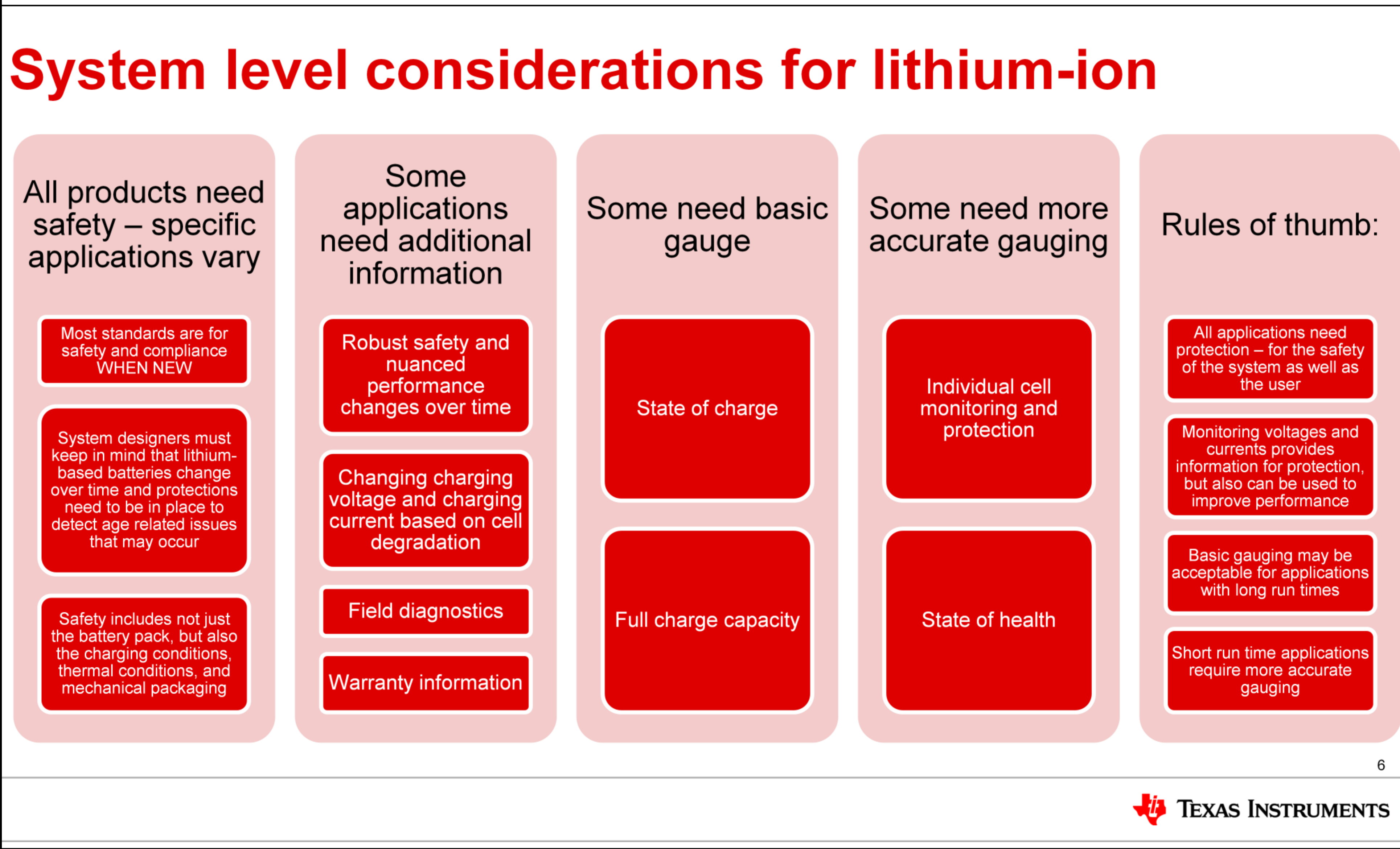
Short circuit	• Addressed by BQ40z80 short-circuit protections
Motor is locked (overload)	• Addressed by BQ40z80 over-current protections
Heating (over temperature)	• Addressed by BQ40z80 over-temperature protections
Charging protection	• Addressed by BQ40z80 smart charge algorithm
Individual cell overvoltage protection	• Addressed by BQ40z80 over-voltage protections
Over charge current protection	• Addressed by BQ40z80 smart charge algorithm

NOTE1: There are additional tests on Li-ion battery charging system and is required to permanently fail the battery pack if the cell voltage is over certain level which are addressed by the FUSE function on the BQ40z80, but the UL2595 calls for redundancy and cannot just rely on a single circuit. This is addressed by the secondary protector BQ771800 on the BQ40z80 EVM schematic.

NOTE2: There is a list of tests to pass the IEC 61000-4-2 standard (the board level ESD). The standard includes functional safety (and software reliability requirement if MCU is used) for the SCF (safety critical function) circuit. If the protection circuit cannot comply with the required tests and ESD, then it has to be evaluated through the function safety requirement. This will be system level and board layout dependent. The BQ40z80EVM schematic has spark gaps and ESD devices, but additional protections may be needed.

Here I give an example of how a single gauge plus protector from TI can provide compliance to UL2595. The standards covers many different topics, and I am highlighting some of them here. The bq40z80 is a multicell gauge and protector for 2S to 7S applications. The device is configurable to meet many different applications, with adjustable settings for short-circuit, over-current, over-voltage, and over-temperature faults. The configuration of the gauge and protection features is important, as incorrect configuration could mean the protection is there, but will not trip when desired. The bq40z80 also address the IATA, air-transport, concerns with an IATA_SHUT bit, where the relative state of charge is checked before entering shutdown. Another useful feature is the IATA_Charge, where in production the device will charge until the RSOC is below the IATA RSOC Threshold, and then disable the CHG FET. This allows for the battery pack to have an acceptable amount of energy to comply with air transport regulations.

In some regulations, a secondary protector is required. On the bq40z80 EVM, the bq771807 is used in conjunction with the bq40z80 to provide this “belts and braces” approach to safety, so that if one protection mechanism fails, another mechanism is still there. The secondary protection method is usually to blow a fus to disonnect the battery from the system.



All products need safety, but specific applications vary. Most of the standards are for safety and compliance when new, however the behavior and perforamance of a battery will change during its lifetime. Lithium based batteries may have specific age-related issues that could cause problems as the battery ages such as forming dendrites due to stresses during charging and discharging, is phyically altered due to swell/contract cycles, is subjected to extreme temperatures or physical stress during use. The basic over-voltage and under-voltage protection may not be nuanced enough to get optimal performance and safety during the life of the battery pack. Additionally, information about the stresses that occur during the life of the product use may be useful for field diagnostics and warranty information. In these applications, a full gauge, in addition to the protection, provides this information such as state of charge, full charge capacity, state of health, individual cell monitoring and protection, and lifetime and black box information.

A general rule of thumb is that advanced gauging is most important for applications that have short run times, as the device may need to squeeze every bit of energy out of the battery during use. A good example is a robot vacuum with a charging dock. In this case, the gauge is not providing the battery state of charge or health information to the user, but to the microprocessor in the system. Accurate gauging and tracking the state of health of the battery is important so that the vacuum robot can maximize the time cleaning, and still be able to get back to the charger to re-charge. If the gauge is not accurate, the vacuum may over-estimate the amount of energy left, and not make it back. Alternately, if the gauge is not accurate, it may underestimate the amount of energy left, and go back to the dock too soon thereby not cleaning as much as possible.

Protection – over-voltage

Why it matters

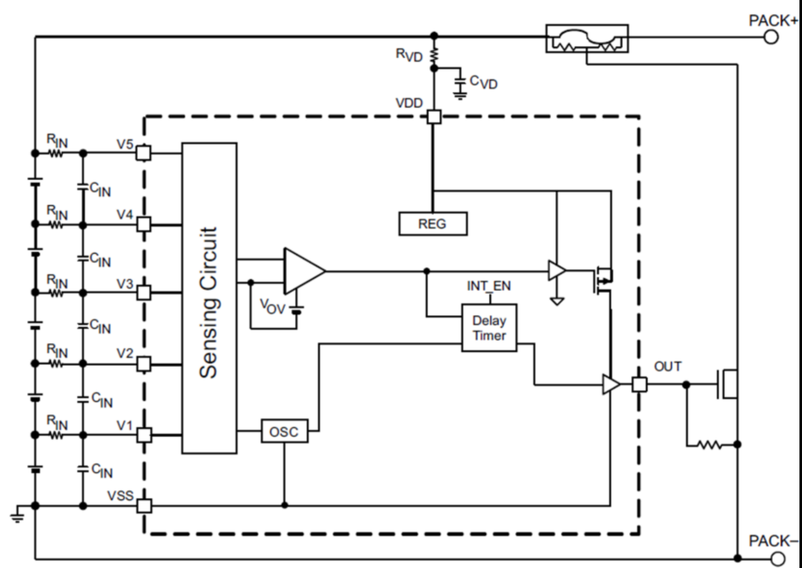
- Charging above the rated voltage causes lithium plating
- Reduction in capacity due to a reduction in the free lithium ions
- Possibility of metallic lithium dendrites causing a short circuit between the electrodes
- Possibility of over-heating

How a protector works

- Monitors each cell voltage in the stack
- The over-voltage threshold depends on the cell chemistry
- The delay, hysteresis and output control for the FET depends on the system

Example of simple protector with COV

- The BQ7718xy series of parts is a simple protector with multiple options
- If a configuration is not yet available, contact your TI representative for possible customization



Part Number	Package	Package Designator	OVP (V)	OV Hysteresis (V)	Output Delay	Output Drive
bq771800	8-Pin QFN	DPJ	4.300	0.300	4 s	CMOS Active High
bq771801			4.275	0.050	3 s	NCH Active Low, Open Drain
bq771802			4.225	0.300	1 s	NCH Active Low, Open Drain
bq771803			4.275	0.050	1 s	NCH Active Low, Open Drain
bq771806			4.350	0.300	3 s	CMOS Active High
bq771807			4.450	0.300	3 s	CMOS Active High
bq771808			4.200	0.050	1 s	NCH Active Low
bq771809			4.200	0.050	1 s	CMOS Active High
bq771811[(1)]			4.225	0.050	1 s	CMOS Active High
bq771815			4.225	0.050	1 s	NCH Active Low
bq771817			4.275	0.050	1 s	CMOS Active High
bq771818[(1)]			4.300	0.300	1 s	CMOS Active High
bq7718xy[(2)]			3.850 – 4.650	Latch, 0.05, 0.25, 0.3	1, 4, 3, 5.5 s	NCH, Active Low, Open Drain, CMOS Active High

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Let's look at a few of the protections for a battery pack. The most basic protection is over-voltage. Why does this matter? For Li-Ion batteries, charging above the rated voltage causes lithium plating, which reduces the capacity due to the reduction in the free lithium ions. There is also the possibility of dendrites forming causing a short between the electrodes.

A protector monitors the cell voltage for each cell in the stack. The over-voltage threshold depends on the cell chemistry and the datasheet parameter of the cell vendor. The delay, heysteresis, and output control for the FET depends on the system configuration.

An example of a high side FET protector is the BQ7718xx series, with many different threshold options. If you don't see one that meets your needs, let us know and we can potentially make one that does.

The devices can be used together to cover 5S through 20S or more applications.

Protection – under-voltage

Why it matters

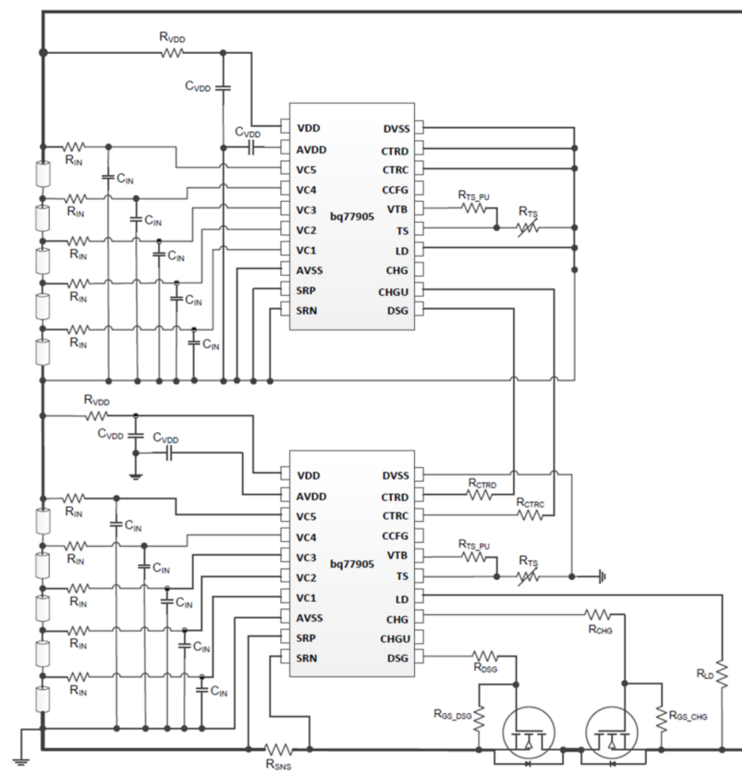
- Lithium ion chemistries can have a breakdown of the electrode materials if over-discharged or stored for extended periods below ~2V (see cell manufacturer datasheets for specifics) – this increases the self-discharge rate
- Below ~2V, copper in the anode current collector is dissolved into the electrolyte. When charged above 2V again, the copper is deposited randomly, potentially causing a short circuit.
- Below ~2V, the cathode may also break down gradually, releasing oxygen by the lithium cobalt oxide or lithium manganese oxide. This results in permanent capacity loss.

How a protector works

- Monitors each cell voltage in the stack
- The under-voltage threshold depends on the cell chemistry
- The delay, hysteresis and output control for the FET depends on the system

Example of a protector with CUV

- The BQ77905xy series of parts is a simple protector with multiple options
- Stackable for high cell count applications
- If a configuration is not yet available, contact your TI representative for possible customization



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The next most common cell protection is under-voltage. Li-ion chemistries can have a breakdown of the electrode materials if they are over-discharged or stored for extended periods of time at too low of a voltage. Because of this, monitoring of the individual cell voltage is needed, and the DSG FET needs to open when the CUV, cell undervoltage, is reached. The cell undervoltage threshold varies depending on the cell chemistry, so again, one protector doesn't fill all applications.

The BQ77905 is a simple protector with multiple options, and is stackable for high cell count applications. Again, if you don't see a version of this part with the thresholds you need for your application, please let us know.

Protection – currents

Why it matters

- Pack terminals can be exposed, and are at risk of being shorted together, so short-circuit discharge (SCD) protection is needed
- Loads may exceed safe operating currents, so over-current discharge (OCD) may be needed
- If a non-approved charger may be used, a separate over-current charge (OCC) may be needed

How a protector works

- Using a sense resistor (R_{SNS}), the voltage across R_{SNS} (V_{SRP}-V_{SRN}) is measured and compared against the thresholds for OCD and SCD

Example of a protector with current protection

- BQ77905xy has two OCD thresholds, and one SCD threshold
- BQ77915xy has two OCD thresholds, one SCD threshold and one OCC threshold

FAULT DESCRIPTOR		FAULT DETECTION THRESHOLD and DELAY OPTIONS		FAULT RECOVERY METHOD and SETTING OPTIONS	
OCC	Overcurrent during charge	5 mV to 80mV (5-mV step)	10 ms	Timer auto-release and load detection, timer auto-release only, load detection only	250 ms or 500 ms
OCD1	Overcurrent1 during discharge	–10 mV to –85 mV (5-mV step)	10, 20, 45, 90, 180, 350, 700, 1420 ms	Timer auto-release and load removal, timer auto-release only, load removal only	
OCD2	Overcurrent1 during discharge	–20 mV to –170 mV (10-mV step)	5, 10, 20, 45, 90, 180, 350, 700 ms		
SCD	Short circuit discharge	–40 mV to –340 mV (20-mV step)	400, 960 µs		

BQ77915xy current protections

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Protection is also needed for excessive currents, especially for high cell count applications where additional power is available. Since pack terminals can be exposed, and are at risk of being shorted together, a short-circuit, or SCD, protection is needed. Sometimes the fault is not due to an external short, but from a resistive failure that can still cause high currents, or an over-current in discharge, or OCD, event. Some applications may also need protection for a fault in the charger, or an over-current in charge, OCC, event protection. To sense the current, the protector or integrated protector-gauge uses a lower resistance sense resistor. The device measures the voltage drop from positive and negative terminals of the sense resistor when current is flowing to determine both the direction and magnitude of the current. This information is used by monitors and gauges for current measurements as well as to disable the CHG and DSG FETs when SCD, OCD, or OCC events occur. Not all protection devices include all three thresholds, and some have multiple thresholds with different response times. Two examples of protectors are shown with the bq77905 and the bq77915. With the bq77915, the OCD thresholds are available with different delay options. If your application needs a specific protection threshold and delay, please contact us.

Protection – temperature

Why it matters

- Under-temperature in charge and discharge (UTC, UTD)
  - Cold temperatures reduce the current carrying capability of the cell, reduce the effective capacity and makes lithium plating more likely
  - It is common to reduce the charge current at cold temperatures – see JEITA for details
- Over-temperature in charge and discharge (OTC, OTD)
  - High temperatures increase the resistances and I2R losses, potentially leading to thermal runaway
  - It is common to reduce the charge voltage at high temperatures – see JEITA for details
  - Thermal runaway is possible if there is positive feedback for current, temperature and resistance increases – potentially dangerous and important to avoid

How a protector works

- NTC thermistors are placed in the system where temperatures may become critical (hot or cold)
- The protector monitors the voltages across the NTC, and calculates the temperature, and takes action based on the threshold set based on OTD, OTC, UTD, or UTC

Example of a protector with thermal protection

- BQ77905 and BQ77915 have OTD, OTC, UTD, and UTC protections
- If a configuration is not yet available, contact your TI representative for possible customization

	Temperature (°C)[1]			
Part Number	OTD	OTC	UTD	UTC
bq7790500	70	50	-20	0
bq7790501[2]	70	50	-20	0
bq7790502	70	50	-20	-5
bq7790503	70	50	-20	-5
bq7790504[2]	70	50	-10	-5
bq7790505	65	45	-20	0
bq7790508	70	50	-20	-5
bq7790509	70	50	-20	-5
bq7790511	65	45	-20	0
bq7790512	65	45	-20	0

Li-Ion cells are complex chemical systems, and like most chemical reactions, they are sensitive to temperature. Unlike Lead-Acid and NiCd, Li-Ion does not like to be charged when cold. Cold temperatures reduce the current carrying capability of the cell, reduce the effective capacity, and makes lithium plating more likely. One standard, JEITA, addresses this problem by mandating that Li-Ion cells not be charged below 0C. However, some battery manufacturers and systems have different requirements, and want the secondary protector to allow charging at a slightly lower threshold, and have the primary protection in a gauge, as well as a smart charger, to take care of the first level of protection for cold charging.

At high temperatures, there is the possibility of thermal runaway, where there is positive feedback for current, temperature, and resistance increasing to a point where it is uncontrollable and potentially dangerous. JEITA also addresses this case, and typicall charge is reduced when temperatures reach 45C. Again, many systems let the primary gauge/protector and smart charger handle this condition, and the secondary protector is there in case of a failure.

The temperature is detected by the protector by sensing the voltage at a pin connected to a negative thremal coefficient thermistor, or NTC. The NTC is placed in the system where the temperatures may become critically cold or hot. As the temperature increases, the NTC resistance decreases, and the protector monitors the voltage across the NTC, calculates the temperature, and takes action based on the threshold set based on the over-temperature in discharge, over-temperature in charge, undertemperature in discharge, and undertemperature in charge.

Many options for the thresholds are possible, and a few are shown here for the bq77905 family.

BQ7718xx, BQ77905, BQ77915 comparison

Protection	BQ7718xy	BQ77905xy	BQ77915xy
Cell over-voltage (COV)	3.85 – 4.65 V	3 – 4.575 V	3 – 4.575 V
Cell under-voltage (CUV)	N/A	1.2 – 3 V	1.2 – 3 V
Over-current discharge (OCD1 and OCD2) For different magnitude and duration	N/A	OCD1: 10 to 85 mV OCD2: 20 to 170 mV Voltage across R_{SNS} (V_{SRP}-V_{SRN})	OCD1: 10 to 85 mV OCD2: 20 to 170 mV Voltage across R_{SNS} (V_{SRP}-V_{SRN})
Over-current charge (OCC)	N/A	N/A	5 to 80 mV Voltage across R_{SNS} (V_{SRP}-V_{SRN})
Short-circuit discharge (SCD)	N/A	40 to 340 mV Voltage across R_{SNS} (V_{SRP}-V_{SRN})	40 to 340 mV Voltage across R_{SNS} (V_{SRP}-V_{SRN})
Over-temperature discharge (OTD)	N/A	65 or 70 C	65 or 70 C
Over-temperature charge (OTC)	N/A	45 or 50 C	45 or 50 C
Under-temperature discharge (UTD)	N/A	-20 or -10 C	-20 or -10 C
Under-temperature charge (UTC)	N/A	-5 or 0 C	-5 or 0 C

In summary, the protector is needed for a Li-Ion based battery pack, and can be used by itself, or as secondary protection with a gauge or monitor. Three different product families are shown here, with the simplest device being the bq7718 family providing cell over-voltage protection only. As with many engineering problems, there are a variety of ways to solve the problem. These families give you choices depending on your system needs.

Monitors

When to use a monitor

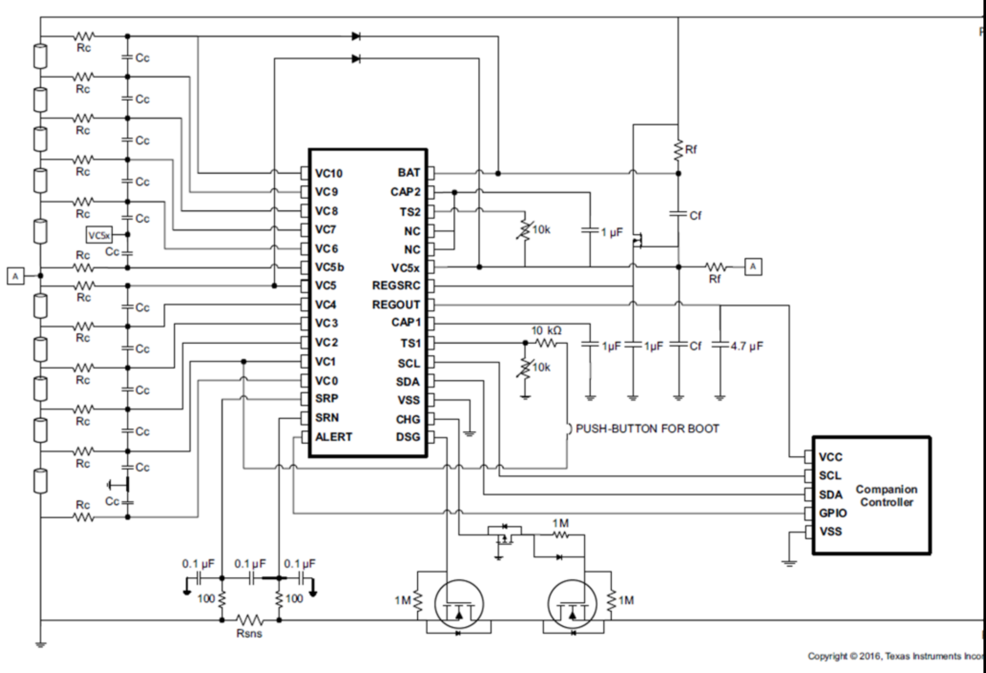
- Do you need to communicate cell voltages and currents to a MCU?
- Do you want more flexibility on thresholds for protections?

What can you do with a monitor?

- Measure individual cell voltages
- Measure current (coulomb counter)
- Cell balancing
- Measure die temperature and external thermistors
- Communicate data and status with an MCU

Also includes protections

- Voltage: OV, UV
- Current: OCD, SCD
- CHG and DSG FET control



BQ76930 monitor with BQ78350 companion controller IC

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Up till now, we have only discussed protectors. All of the protectors are stackable, so they can be scaled to meet the cell count needed in the systems we discussed. The protectors we discussed are usually the second level of protection, and the first level of protection comes from a monitor or a gauge. If you want to communicate the cell voltages and currents to a MCU for system level decisions, but don’t need a pre-packaged gauge solution, then a monitor may be the righ choice. If you need more flexibility on the thresholds and timing for the protections, both a monitor and a gauge+protector will give you that ability.

Using the example of the BQ769x0 family of monitors, these devices provide a way to measure the individual cell voltages, current, provide cell balancing, die temperature, AND they are able to communicate this information to a MCU.

That sound like a lot of information, and it is. It can be used to gauge system perforamnce, diagnostics, and estimate run time. However, the gauging function is not done with a monitor.

Gauge

What can a gauge do in your system?

- Provides an estimate of remaining charge in the battery during use
  - Options for load type, smoothing function, temperature
- Provides an estimate of present charge during charging
- Provides accurate current and voltage data during operation
  - For system optimization
  - For display to the customer
  - For diagnostic and characterization during development
- Determines aging: state of health = full charge capacity / design capacity
  - For replacement or warranty determination
- Is a black box recorder
- Authentication of battery
- Enhances safety

So the next question is – what can I do with a gauge? With the bq769x0 family of monitors, there is a companion CEDV gauge available called the bq78350-R1. This gauge provides and estimate of the remeaingn charge in the battery during use, and can be tuned for the type of load, how the information is displayed and reported, and for the operating environment. The gauge also provides an estimate of the charge in the battery during charging.

Some gauges are able to provide information about the state of health, as well as record critical use inforamtion, called lifetime data, as well as be a black-box recorder to inspect what happened during a permanent fail event. Not all gauges behave the same, or have the same features, and like the protectors and monitors, TI provides several different solutions for gauging high cell count applications.

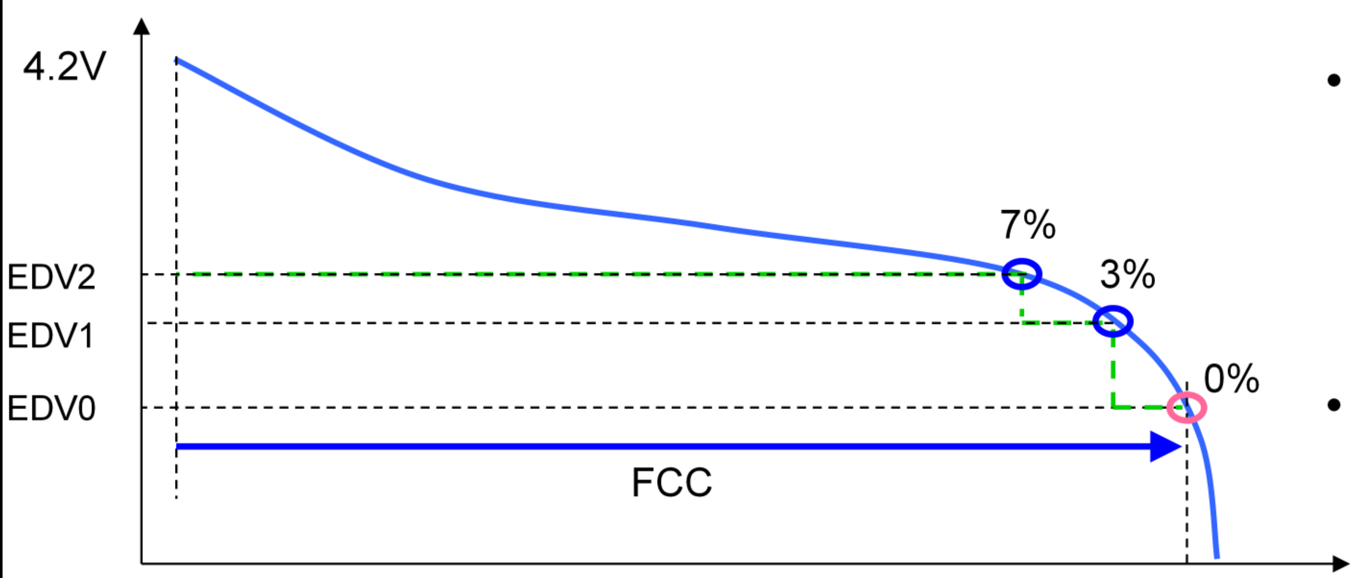
Gauging algorithm options

- Compensated end of discharge voltage (CEDV)
- Impedance Track™ (IT)
  - Highly accurate
  - System or pack topology

Before I get into the specifics of the high cell count gauging solutions, allow me to briefly cover the difference between two gauging algorithms from TI. Compensated End of Discharge voltage, or CEDV, is one algorithm. Impedance Track, or IT, is the second algorithm. Each has benefits and constraints, so a little backtround may be useful.

CEDV learning before fully discharged

Fixed voltage thresholds



- It is too late to learn when 0% capacity is reached → learning FCC before 0%
- We can set voltage threshold that corresponds to given percentage of remaining capacity
- However, true voltage corresponding to 7% depends on current and temperature

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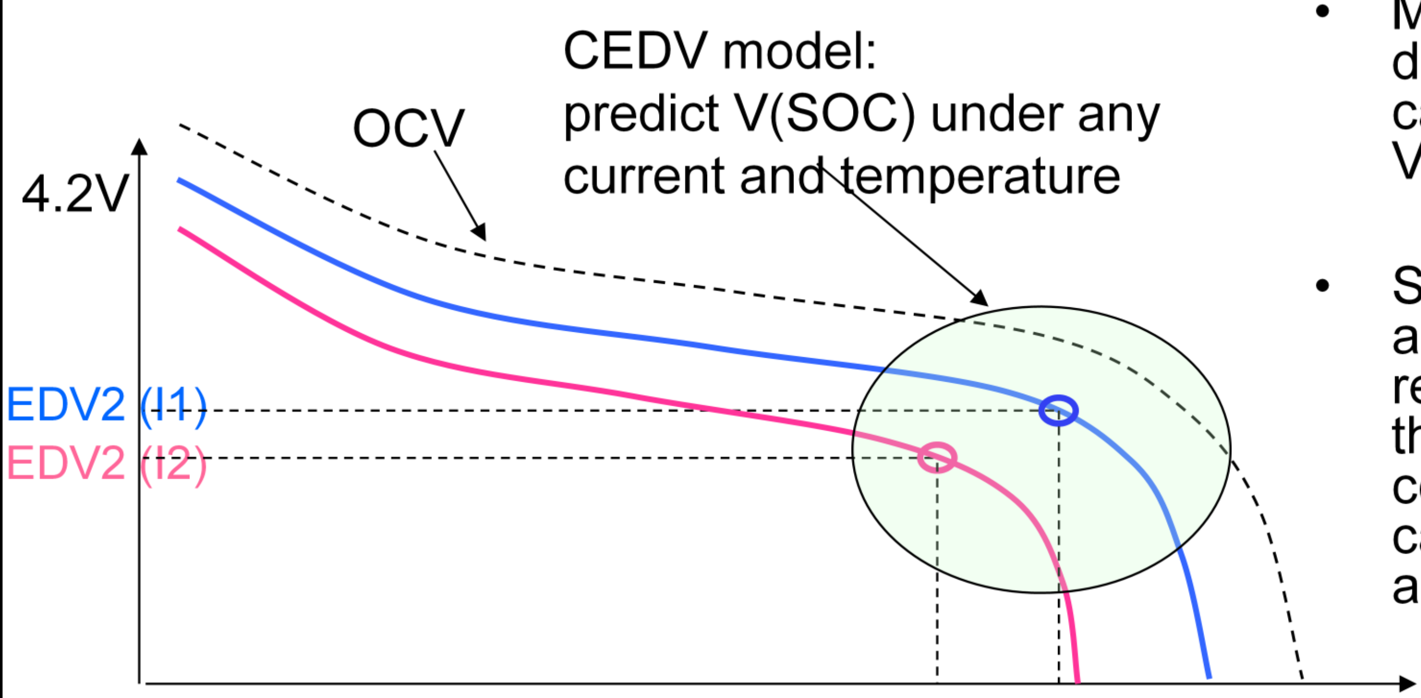
CEDV uses current integration for gauging. The gauge has accurate information about the amount of energy into and out of the battery. The CEDV algorithm calculates the 7% and 3% remaining state of charge values in real time based on load and temperature. This way, the user is alerted prior to the battery reaching zero. There is a complex formula that takes into account self discharge and temperature effects. This method, of course, relies on learning full charge capacity by discharging the battery below 7% at least occasionally, which is one constraint of CEDV gauges.

CEDV learning before fully discharged

With current and temperature compensation



- Modeling last part of discharge allows to calculate function V(SOC, I, T)
- Substituting SOC=7% allows to calculate in real time CEDV2 threshold that corresponds to 7% capacity at any current and temperature

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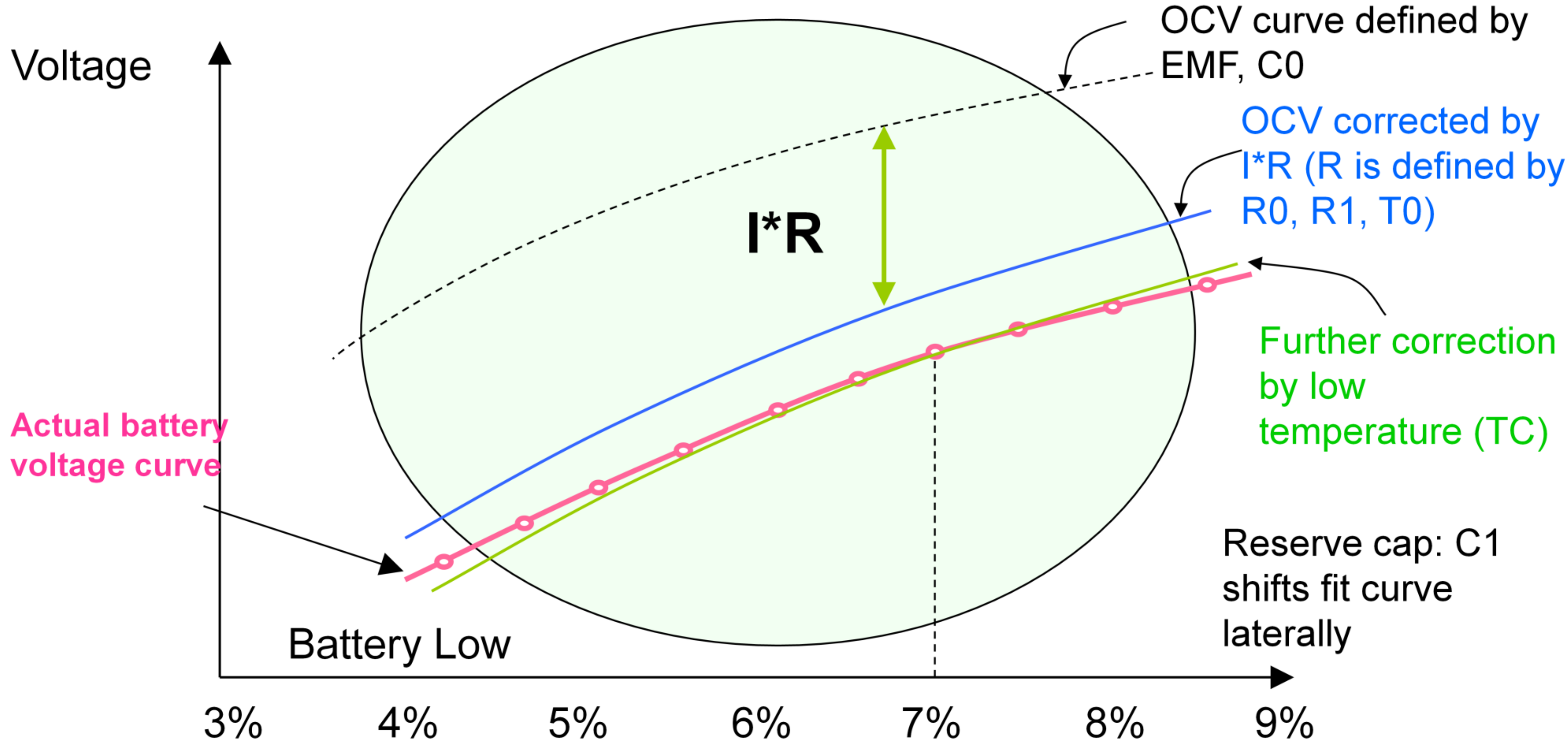
Since temperature and self-discharge current also impacts the amount of available energy in the pack, the model needs to account for these variables as well. Here you can see the calculated 7% value under different discharge currents, with one curve shown in pink and the other in blue. The model uses the present state of charge, current, and temperature to estimate the SOC=7% value under these different conditions.

CEDV model visualization



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TEXAS INSTRUMENTS

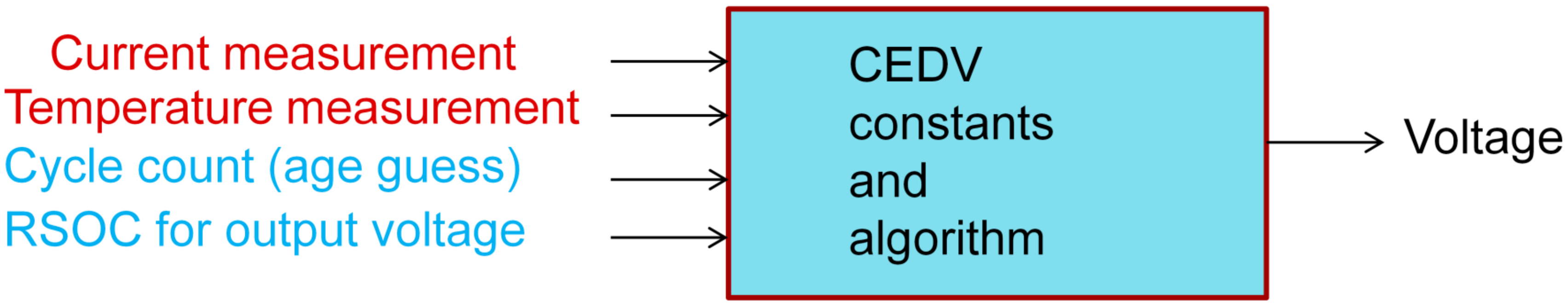
There are 7 key parameters that affect the performance of the CEDV gauge. These parameters are defined by modeling the cell over two different current levels and three different temperatures. Parameters EMF and C0 define function to calculate the open circuit voltage using the existing state of charge and temperature.

Parameters R0,R1 and T0 define the cell resistance based on the state of charge and temperature. R1 defines the slope of the resistance based on the state of charge, R0 the magnitude of the resistance, and T0 the slope of resistance dependence on temperature.

Parameter TC defines additional resistance increase at temperatures below 21ºC:

Parameter C1 allows to shift whole function to the left. In this case, EDV2 is reached earlier and so reserve capacity is provided. 1 Unit of C1 shifts function by 0.39%

CEDV summary



The seven constants describe:

- OCV curve shape
- Temperature effect on OCV
- Resistance
- Temperature effect on resistance
- Low temperature effects
- Aging properties
- Reserve capacity

In summary, the CEDV gauge takes current integration and seven constants that describe the battery and system behavior to provide an estimate of the SOC for the battery pack. Characterizing the cell for CEDV, as well as requiring periodic full charge–discharge cycles are requirements for accurate gauging with a CEDV gauge. Also, the aging of the battery is only approximated, and is estimated by compensating the cell resistance based on cycle count.

Fuel gauging – Impedance Track^{TM}

Cell voltage measurement

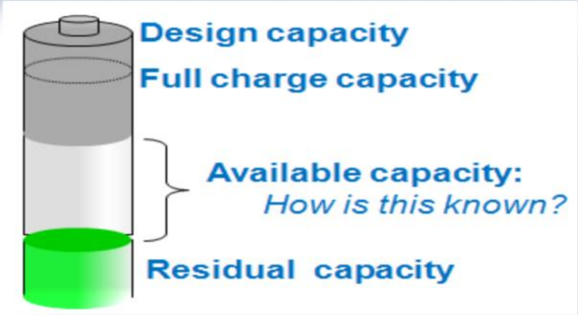
- Measures cell voltage
- Advantage: simple
- Not accurate over load conditions

Coulomb counting

- Measures and integrates current over time
- Affected by cell impedance
- Affected by cell self discharge
- Standby current
- Cell aging
- Must have *full to empty* learning cycles
- Must develop cell models that will vary with cell maker
- Can count the charge leaving the battery, but won't know remaining charge without complex models
- Models will become less accurate with age

Impedance Track™

- **Directly measures effect of discharge rate, temp, age and other factors by learning cell impedance**
- **Calculates effect on remaining capacity and full charge capacity**
- **No host algorithms or calculations**
- Impedance Track Whitepaper



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TEXAS INSTRUMENTS

Now let's look at an Impedance Track gauge, and see how it is different. The CEDV gauge utilized coulomb counting, which does not account directly for cell impedance changes during aging, self-discharge, must have full-to-empty learning cycles, must develop a cell model with every cell maker, and although charge entering and leaving is measured, the total energy is still dependant on a complex model which becomes less accurate with cell aging.

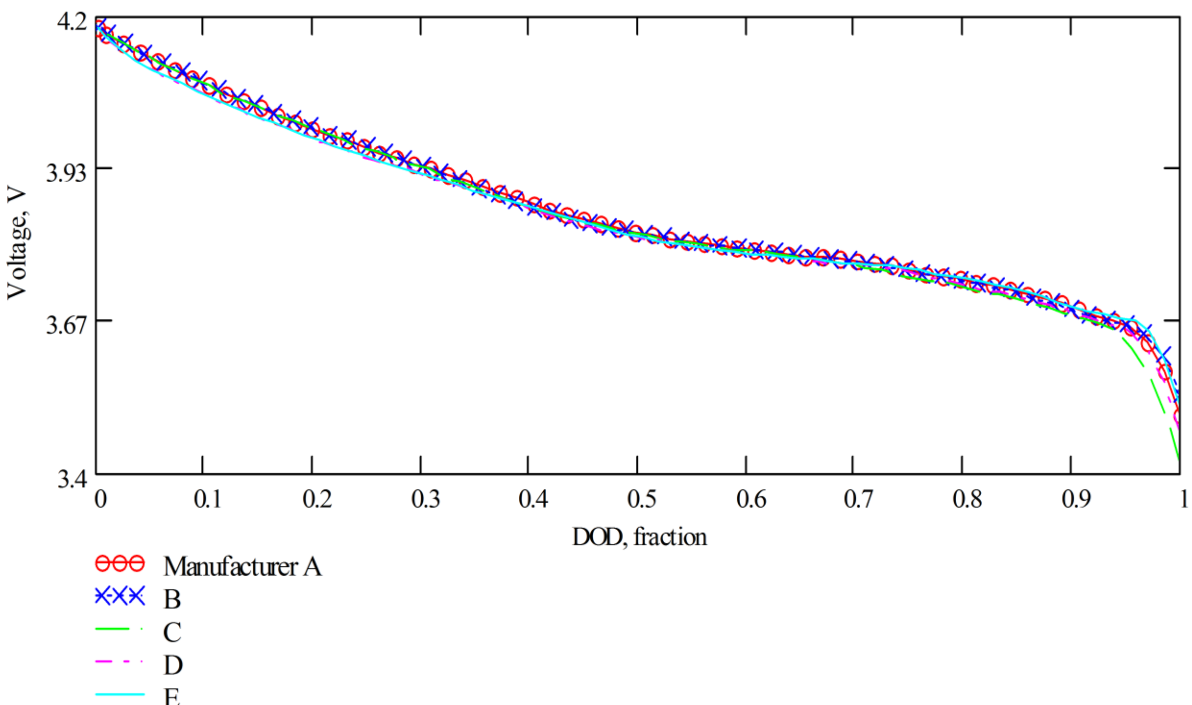
Impedance track directly measures the effect of discharge rate, temp, age and other factors by learning cell impedance. This allows a calculation of the remaining capacity and full charge capacity, which changes as the battery changes.

IT gauging definitions

- OCV – open circuit voltage
  - relaxed or predicted voltage with no load
- DOD – depth of discharge
  - 0% is charged to the brim, 100% is completely empty of energy
  - Does not depend on load or temperature or system characteristics
- RM – remaining capacity in mAh
  - Usable capacity of the battery from current DOD to empty
- FCC – full charge capacity in mAh
  - Usable capacity of the battery from full to empty
- SOC – state of charge, 0% - 100%
  - Full and empty points depend on the system
  - Can change with load and temperature
  - SOC = RM / FCC

Before going into Turbo Mode too much, let's review some of the terms for gauging. The open circuit voltage is the voltage that the cell will reach when completely relaxed with no load or charge. The depth of discharge is and indicator for how empty the system is, and does not depend on load ro temperature or system. The remaining capacity is the usable capacity of the battery from the present depth of discharge to empty. The full charge capacity is the usable capacity from full to empty. This is different than design capacity, which is the capacity on the cell datasheet. The full charge capacity is dynamic and learned over time. The state of charge is what most people expect to see on the device, and shows the remaning capacity divided by the full charge capacity, giving a percent value.

OCV (open circuit voltage)



https://training.ti.com/chemistry-id-matching-online-gpc-tool

- OCV profiles can be very consistent if base electrode chemistry is the same
- Most voltage deviations from average are below 5mV
- Average DOD prediction error based on average voltage/DOD dependence is below 1.5%
- Same OCV database can be used with batteries produced by different manufacturers as long as base chemistry is same
- Generic database allows significant simplification of fuel-gauge implementation at user side

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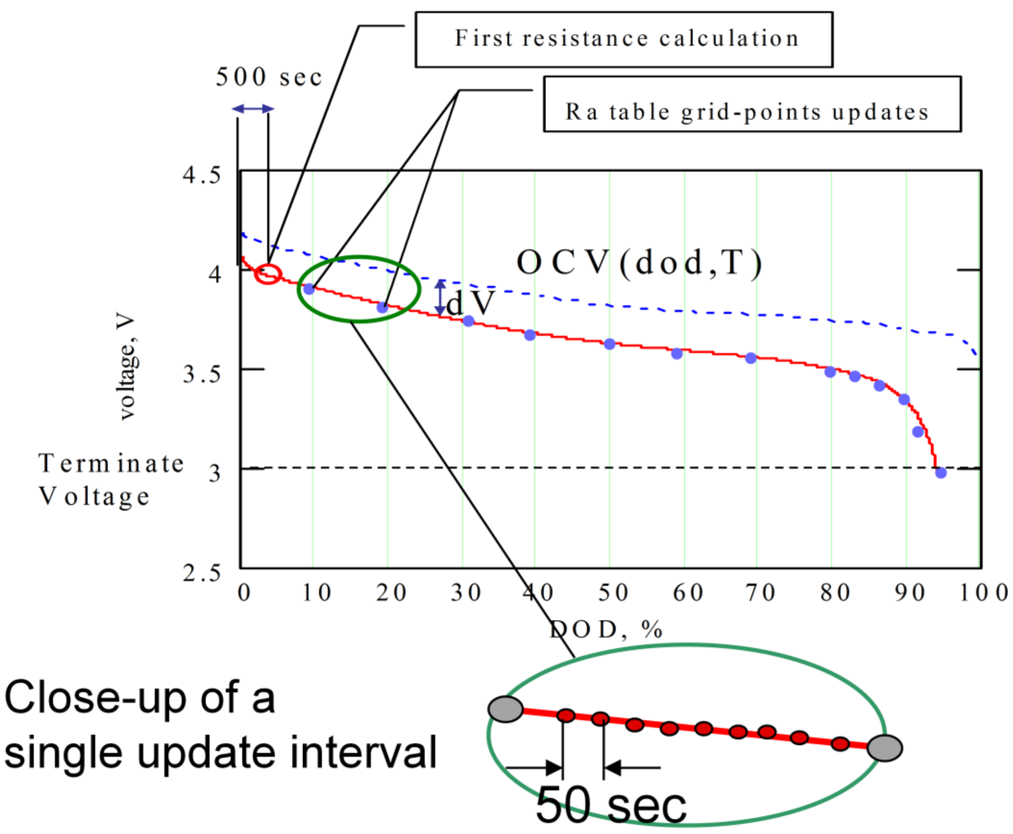
TEXAS INSTRUMENTS

The open circuit profile of cells is fairly consistent if the cells are made the same way. Here is data showing the discharge curve for five different manufacturers. Most of the voltage measurements were withing 5mV of each other. Since the open circuit voltage database can be used with different manufacturers, a generic database allow significant simplification of fuel-gauge implementation at the user side. These cell profiles are called ChemIDs by TI, and they are availalble through our gauge tools. Also, you can use a tool called GPChem tool. Click on the link provided to see a tutorial on how to use the tool to match your cell with the TI database of cells.

Resistance update process



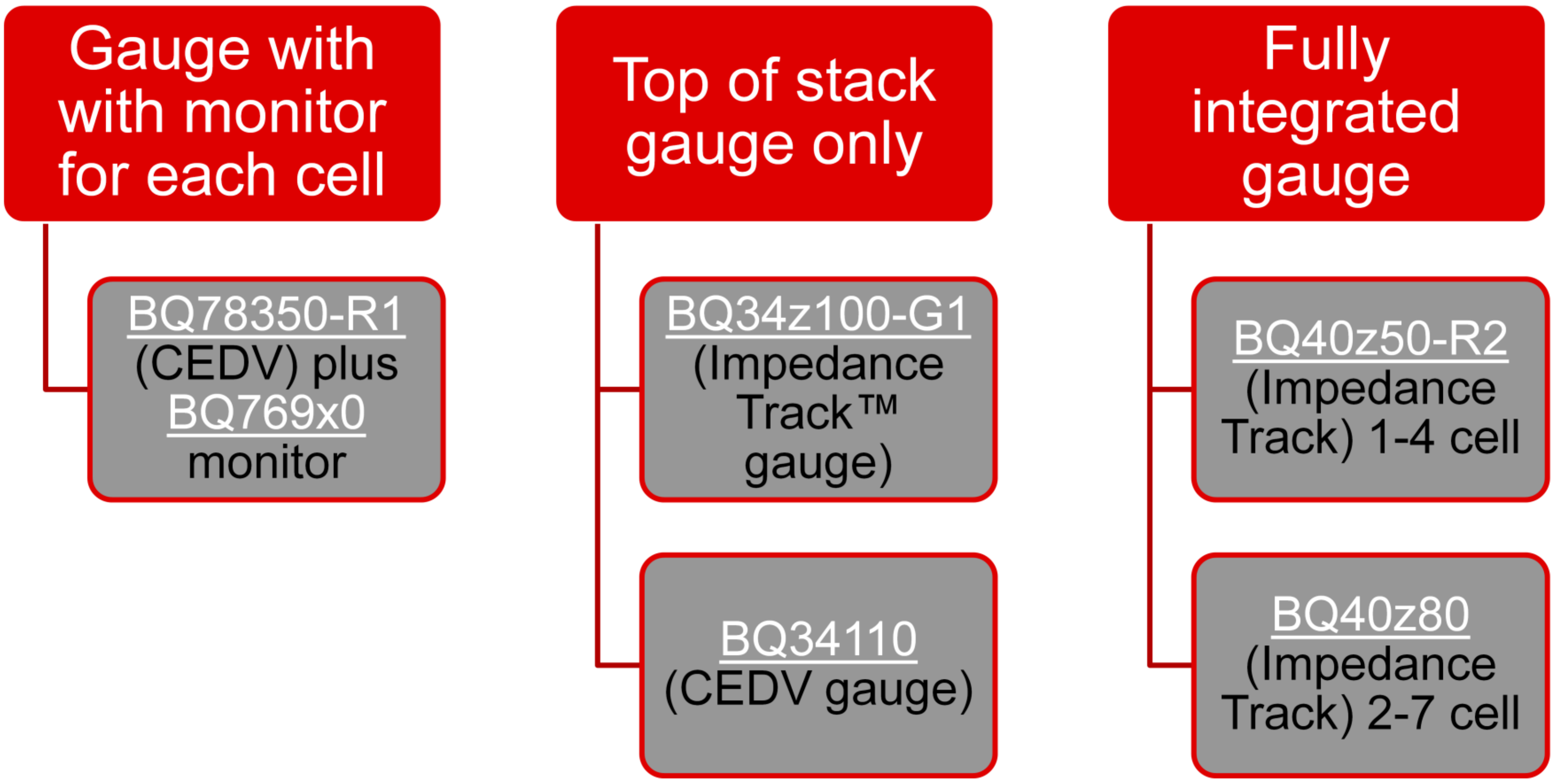
- The resistance in data flash (Ra table) is updated after 10% (and after 80% DOD after 3%) intervals of DOD
- During entire interval (for example from 50 to 60% DOD) we take resistance measurements every 50 sec and store them in RAM
- Many resistance measurements are stored in RAM before GG reaches an actual grid-point (for example DOD exceeds 60%) and makes an update of Ra in data-flash by doing linear regression from the points stored in RAM

Resistance updates in RAM

TEXAS INSTRUMENTS

The Impedance Track algorithm uses the chemID as a starting point for the resistance table, and the table is updated during chartge and discharge cycles. The gauge needs to complete at least one full learning cycle prior to shipping to have the most accurate gauging at the start of customer use. During the discharge cycle, the resistance table, Ra table) is updated and stored in RAM. This table is then used to better predict the state of charge. The updating process happens naturally during the use of the product, and reflects the actual parameters of the cell during the life of it's use.

Gauge topologies



Texas Instruments

So now let’s look at a few high cell count gauge approaches. The first is a gauge with a monitor for each cell. This can be done with the BQ78350-R1 as the CEDV gauge, and the BQ769x0 devices for the monitor/protector for up to 5S, 10S, or 15S applications.

The second approach is a top-of-stack gauge where the individual cells are not monitored by the gauge. A protector is usually used with this approach. The BQ34z100-G1 is the Impedance Track version of this architecture, and the BQ34110 is the CEDV version.

If you need a fully integrated gauge with individual cell monitoring and primary protection, as well as gauging, then the bq40z50 or bq40z80 is the right approach. These gauges improve the accuracy of the gauging, reduce the size, and provide flexibility in protection and performance.

BQ78350-R1

Companion Fuel Gauge for bq769xx family of front end monitors

BQ78350-R1 Features

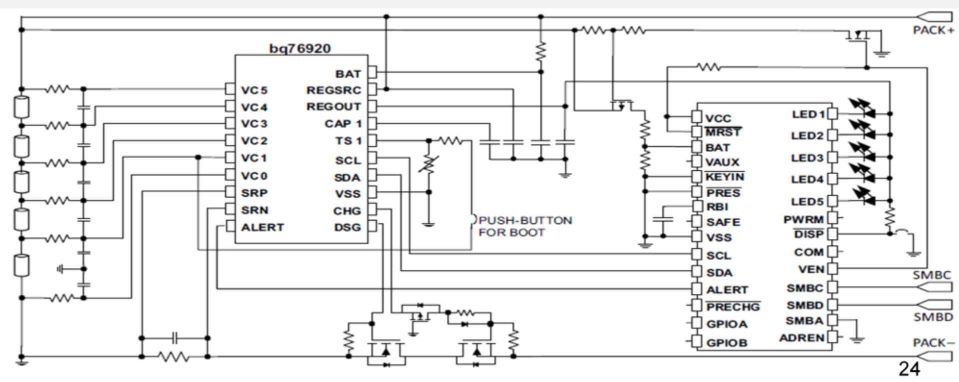
- Compensated EDV coulomb counting based gauging algorithm
- Integrated voltage, current and temperature protections
- Voltage–based cell balancing algorithm
- Supports batteries up to 320 Ah
- Supports charge/discharge currents to 320 A
- State of Health indication
- Lifetime data logging
- LCD or LED display support (3-5 segment)
- Low–power storage mode ICC of 8 μA
- SHA–1 authentication
- SMBus communication interface
- 30–TSSOP (DBT)

Benefits

- Supports high cell/high current/large capacity battery packs
- Enables fastest time to market with NO customer algorithm or F/W development needed
- Fully compatible with bq76920, 930, 940 for 3-15s packs
- Extremely simple setup and configuration for CEDV
- Chemistry parameters can be self-tuned by customer without needing TI's support
- Improves safety with comprehensive protection
- Cell balancing maximizes run time and cycle life
- Visual display of SOC with LED/LCD
- Lifetime data supports warranty claim verification
- battery replacement decisions facilitated by SOH indication
- TSSOP package suitable for industrial application

Applications

- Light electric vehicles (LEV): eBikes, eScooters, Pedelec and pedal–assist bicycles
- Cordless household appliances and power tools
- Battery backup/UPS systems
- Wireless base station backup
- Telecom Power systems
- General 12–48V battery packs
- Compatible 2nd Level Protectors: bq7718, bq7716



TEXAS INSTRUMENTS

The BQ78350-R1 is the companion fuel gauge for the BQ769x0 family of monitors that we have previously discussed. This is a CEDV based gauge that supports high cell and high current battery packs. The algorithm is completely self contained, and does not require a separate MCU to run any FW. The monitor provides all the voltage and current information required to execute the CEDV algorithm with a simple two-chip solution that is scalable from 3S to 15S. This gauge supports batteries up to 320Ah, with charge/discharge curent up to 320A. Lifetime data logging of critical parameters, state of health indication, and support for LCD or LED display. We haven't discussed authenticaion, which is a whole other presentation, but this gauge also support SHA-1 authentication to enable the creation of battery packs that can only be used with specific end equipment. This is important for some applications where the entire system needs to be guaranteed safe and compatible, such as eBikes, eScooters, hoverboards, etc.

Gauge topologies

Gauge with with monitor for each cell
- BQ78350-R1 (CEDV) plus BQ769x0 monitor

Top of stack gauge only
- BQ34z100-G1 (Impedance Track™ gauge)
- BQ34110 (CEDV gauge)

Fully integrated gauge
- BQ40z50-R2 (Impedance Track) 1-4 cell
- BQ40z80 (Impedance Track) 2-7 cell

BQ34110

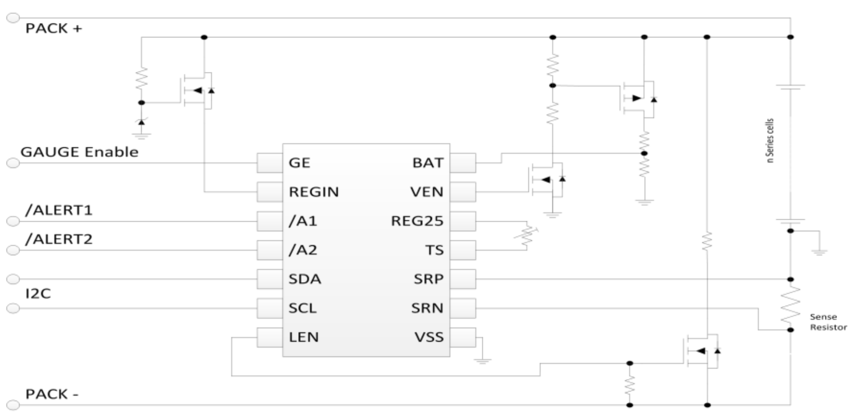
Multi-chemistry gas gauge for rarely discharged applications

BQ34110 Features

- CEDV fuel gauge only for **Li-ion, polymer, LiFePO4, NiMH and lead acid**
- Rarely discharged **application end-of-service**/state-of-health determination
- **Large capacity** batteries supported (>65Ahr)
- **High current** applications supported (>32A)
- Suitable for packs **2.5V to ~65V**
- Low operating current of <140µA with <64µA in sleep
- External 103AT NTC thermistor supported
- Two-wire (**I2C**) communications
- Configurable warning (/A1,/A2) outputs
- 14-pin TSSOP

Benefits

- Enables end-of-service determination without risking guaranteed service time/large discharges
- Very simple setup configuration
- Multiple chemistry support
- Accurate fuel gauging
- Independent of protection solution and cell balancing requirements
- Capable of gauging very high series cell batteries



Applications

- Battery backup applications
- UPS
- Asset tracking

TEXAS INSTRUMENTS

The BQ34110 is a top of stack gauge that uses the CEDV algorithm. It only monitors the higest voltage in the pack, divided down and presented to the ADC, and also has a second ADC as a dedicated coulomb counter for current integration. One of the unique features about the BQ34110 is the end of service state of health determination for rarely discharged applications such as battery backup applications. For these applications, they do not go through the typcial charge/discharge cycles that allow the gauge to determine the state of health of the battery. In this case, there is a very small, adjustable discharge level that allows the gauge to determine if the state of health of the battery has degraded during it's use to a point where it can not guarantee the delivery of the rated power for the rated duration. For example, a battery back up system may guarantee a certain power for 100s, and when the system is not longer able to deliver that, the BQ34110 will indicate this information to the host. The BQ34110 can be used in conjunction with monitors or protectors as needed to meet the safety and compliance standards for these applications.

BQ34z100-G1

Multi-chemistry Impedance Track™ fuel gauge

BQ34z100-G1 Features

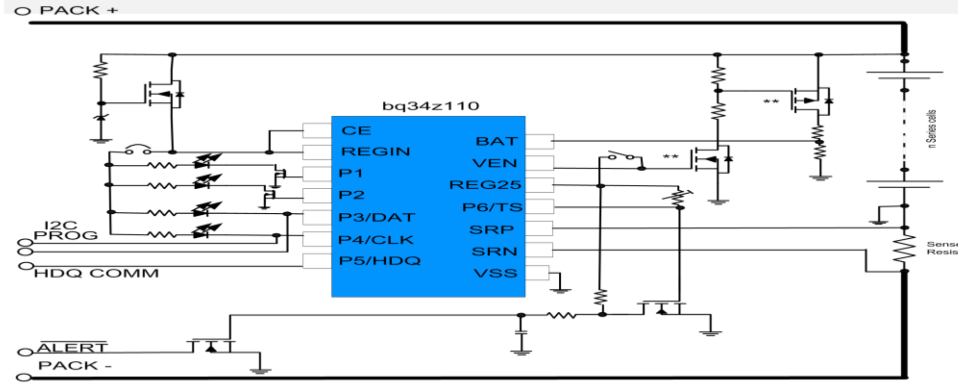
- Impedance Track™ fuel gauge capacity estimation for Li-ion, polymer, LiFePO4, PbA, NiMH and NiCd
- Large capacity batteries supported (>65Ahr)
- High current applications supported (>32A)
- Suitable for packs 2.5V to ~65V
- Low operating current of <140µA, sleep <64µA
- SHA–1 authentication
- External thermistor supported
- Optional interfaces
- Single wire (HDQ) / two-wire (I2C) communications
- 1 or 4 LED display – more with expander IC
- Configurable warning signal
- 14-pin TSSOP

Applications

- Energy storage systems
- Battery backup, UPS and wireless base stations
- Power assist, eBike
- Cordless home appliances
- General 12–48V battery packs

Benefits

- Add-on gauge that can be added to a wide variety of high cell / large capacity / high current packs
- Independent of protection solution and cell balancing requirements
- Resistor divided pack level gauging with good accuracy
- Single wire HDQ saves on connector pin cost
- Authenticates only legitimate packs for overall system safety
- No customer algorithm or F/W development needed, enables fastest time to market
- LED display of capacity for visual indication
- TSSOP package suitable for industrial application



** optional to reduce voltage divider power consumption

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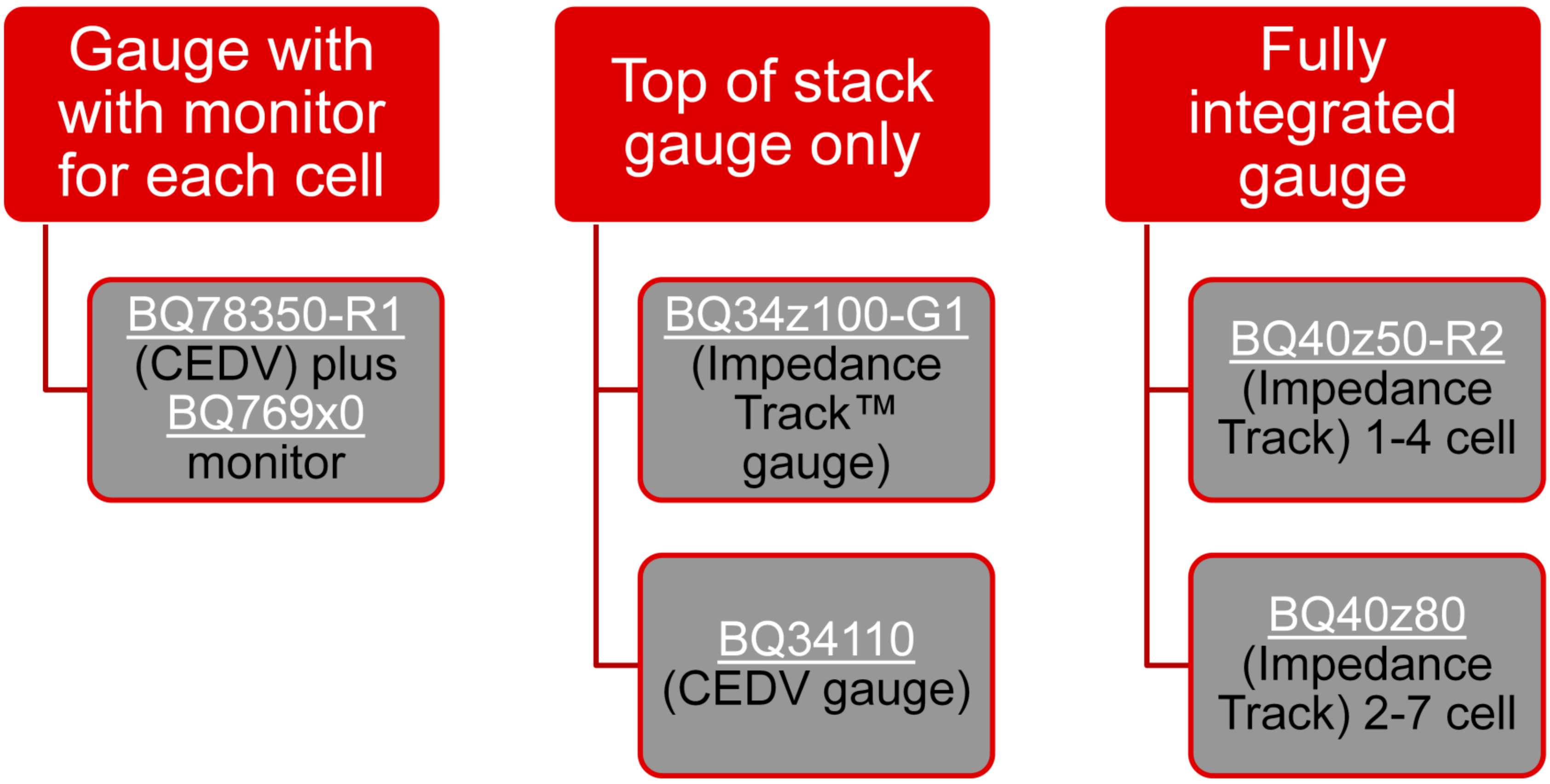
Texas Instruments

The BQ34z100-G1 is the impedance track version of the top of stack gauge, and has the added accuracy benefits that impedance track provides. Impedance track is specifically useful for LFP, or lithium iron phosphate battery packs, as these have a very flat OCV curve. The IT algorithm takes this into account during the resistance table updates, which provides a high accuracy for LFP battery packs.

Gauge topologies



Texas Instruments

BQ40z50-R2

1S – 4S SBS 1.1–compliant gas gauge and protector

BQ40z50-R2 Features

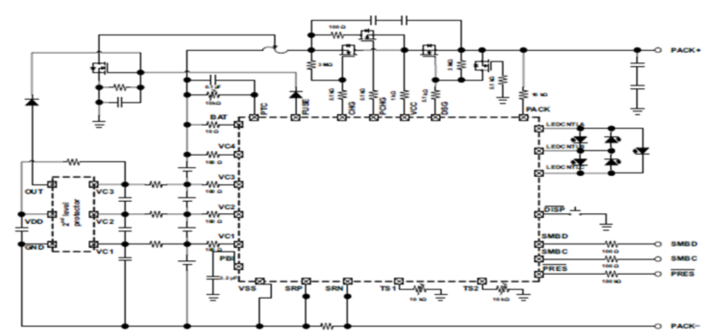
- Integrated AFE safety protector
  - Programmable
  - Voltage, current, temperature, cell imbalance
- Advanced IT gauging with JEITA & additional temp and current sub-ranges & cell balancing at rest or while charging
- Turbo mode data support
- Black box recorder
- N–channel FET drive
- Integrated 1.8V LDO
- SHA–1 authentication
- LED (up to 5) support option (BQ40z50)
- 4mm x 4mm x 0.9mm 32L–QFN

Benefits

- High gauging accuracy & multiple complex charging profile support
- Provides comprehensive protection for multicell safety
- Continuous cell balancing ensures maximum battery capacity is available at all times
- Turbo mode reports maximum power available at any time
- Lifetime/black box supports analysis of returned battery packs
- Reduce BOM count/lower BOM cost
- Anti-counterfeiting
- Visual display of SOC with LED indication

Applications

- Notebook/netbook PCs
- Medical and test equipment
- Portable robotics
- Portable instruments
- Drones
- Cordless household appliances
- Compatible 2nd level protectors: BQ2961/2, BQ2947, BQ2945



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TEXAS INSTRUMENTS

The BQ40z50 is a fully integrated gauge for up to 4S battery packs. It uses the latest Impedance Track algorithm, and is available in a small 4mm by 4mm then QFN package. This device is the work-horse for most notebook battery packs, and we are about to release the bq40z50-R3, which has updates to some of the key features of this device. The bq40z50-R3 is a firmware only release, and can be flashed onto bq40z50-R2 hardware. One of the features unique to the BQ40z50 devices is the support of Turbo Mode, also known as Intel Dynamic Battery Power Technology, DBPT. The BQ40z50-R2 supports DBPTv2, the the bq40z50-R3 support DBPTv3. This algorithm calculates a 10s sustained peak power and current, as well as a 10ms max peak power and current. This allows the system to know what power levels it can achieve without hitting critical voltages at the cell level, pack level, and system level, and can be tuned to individual systems. This guage family is full features with t comprehensive protection for multicell safety, and is compatible with second level protectors.

BQ40z80

2S – 7S battery gas gauge with protector

BQ40z80 Features

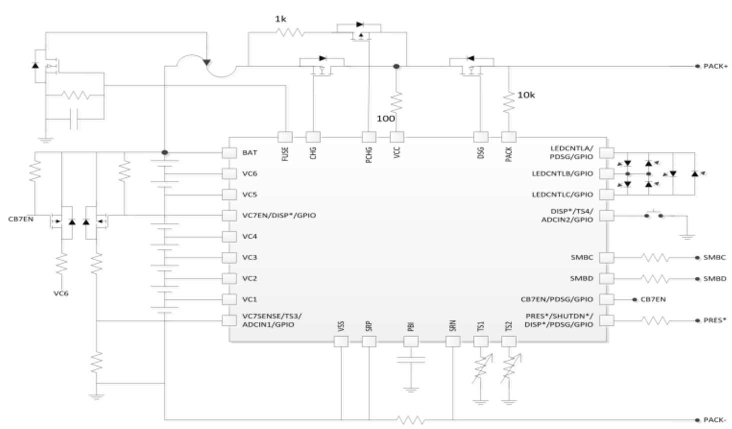
- Battery manager with 2-series to 7-series capability
- Advanced Impedance Track™ gauging with JEITA charge control and cell balancing during charge or at rest
- Suitable for Li-ion, LiFePO4 and NiXX chemistries
- Integrated safety protector with high-side NMOS FET drivers
  - Voltage, current, temperature, cell imbalance
- LED support (up to 6)
- Pre-charge and pre-discharge modes included
- Integrated flash memory and lifetime/black box support
- Elliptic curve cryptography (ECC) authentication
- Precision analog front end with two independent ADCs
  - High-resolution, 16-bit coulomb counter
  - 15-bit delta-sigma ADC with multiplexer
  - Support for simultaneous CC and ADC
- QFN 32-pin package (4mm x 4 mm x 0.9mm)

Applications

- UPS, backup, and energy storage systems
- Cordless appliances
- Non-military drones
- Portable robotics
- Compatible 2nd level protectors: BQ7718, BQ7716

Benefits

- High gauging accuracy & multiple complex charging profile support
- Provides comprehensive protection for multi-cell safety
- Continuous cell balancing ensures maximum battery capacity is available at all times
- Lifetime/black box supports analysis of returned battery packs
- Anti-counterfeiting
- Visual display of SOC with LED indication



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Texas Instruments

The BQ40z80 is similar to the BQ40z50, but has expanded capabilities to support from 2S to 7S battery packs, keeping the same small 32-pin 4mm by 4mm thin QFN package. This part will support higher cell cound applications like cordless vacuums, vacuum robots, drones, portable robotics, and battery backup systems. A future version will incorporate the end of service indication for rarely discharged applications. The BQ40z80 brings some unique features that help it be more configurable for industrial applications.

BQ40z80 functions

Gauging

- Impedance Track Gas Gauging
- Scaling for higher current NEW
- Support for up to 32V stack voltage (35V abs max) NEW
- Support for 1mΩ sense resistor NEW

Flexible I/O NEW

- Up to 4 TS inputs
- ADC Inputs
- /DISP
- /PRES
- GPIO
- PDSG
- LED Pins
- CB7EN

Authentication NEW

- Elliptic Curve Cryptography (ECC) or SHA-1

GPIO INT Modes NEW

- Battery Mode
- Battery Status
- Charging Status
- Temp Status
- Gauging Status
- IT Status
- Safety Status
- PF Status

Charging

- JEITA-based Charging OR Dynamic Charge Adjustment Based on Cycle Count or State of Health
- SMBus Broadcast to a Smart Charger

Protection

- Voltage, Current, Temperature, and Cell Imbalance
- High-Side NFET Drivers
- Fuse Drive Capability
- Pre-charge and Pre-discharge Modes Included

Calibration

- CELL Gain
- VC6-VSS Gain NEW
- PACK Gain
- 7th CELL Gain NEW

Logging

- Lifetime Data
- BlackBox Functionality

TEXAS INSTRUMENTS

This chart shows all the new features built on top of the BQ40z50 base functionality. Because the BQ40z80 is scaled up to 7S, it naturally makes sence that high current packs will also be developed with this part. The device can natively support pack capacities up to 29Ah and battery currents up to 32A. With current scaling, the scale factor can be set between 0 and 100, with the scaled current still in 1mA resolution. To reduce losses in the sense resistor, a 1milli-Ohm typical sense resistor is supported, but this can be smaller if larger currents are used.

The BQ40z80 has several multi-function pins that can be configured based on the specific application needs. Most unused pins can be configured as GPIO's, with a the capability of generating interrups on pins through a flag mapping function. The flags may be OR'd or AND'ed together to trigger an interrupt on a particular GPIO pin, with up to eight different flags OR'ded onto a single pin.

Other multi-function pin functions are additional ADC inputs to monitor voltages or temperatures, a dedicated display pin to turn on the LED's, and a presence pin to use for removalbe battery applications to assist in battery detection and entering/exiting lower power states.

A new feature is a pre-discharge pin, which is useful when the load is highly capacitive, such as a motor. The pre-discharge pin allows charging up the cap until a pre-determined voltage is reached, and then turning on the DSG FET. This reduces the chances of having the battery OCD and SCD protections trip when turning on the load, as soft-starts the load and reduces the current spike.

The BQ40z80 also improves the authenitcaion capabilities with Elliptic Curve Cryptography, or ECC, as the encryption method for authentication.

Want to know more about the BQ40z80?

Stay for the detailed presentation next!

If you'd like to see more about the BQ40z80, make sure to see the presentation on the BQ40z80 deep dive, where I go into specific problems that can be solved with this device. That sums up the design considerations for high cell count applications. I hope I've given you things to consider when designing the battery pack and protection for your system, as well as a few devices from TI that can help you meet your design goals.