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APPLICATION NOTE 6378

HOW TO MONITOR STATE-OF-CHARGE IN SMALL BATTERIES WITH TINY, ULTRA-LOW-POWER COMPARATORS

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Abstract: Many of today's portable consumer electronic devices are powered by small button- or coin-cell batteries. Users, of course, expect long battery life and reliable charge-level information. However, it can be quite challenging to efficiently monitor the health and state-of-charge (SOC) of these batteries without significantly affecting said SOC. In this application note, learn how simple, low-power monitoring circuits for small batteries can address this challenge.

Monitoring Battery Voltage and Temperature

Systems engineers have an important task when it comes to budgeting their design's power requirement. Looking at the system as a whole, microcontrollers/microprocessors serve as the "brains" managing the system reliably and performing the required functions. The typically power-hungry controller is the system’s workhorse, so it does not make sense to have the controller do all the work. To prevent system power dissipation, the controller needs to remain in a sleep state for extended periods as it seeks out flags present in the GPI pins.

For continuous monitoring of the system's vital functions, many engineers are turning to low-power circuits. These circuits flag the micro (usually in the form of interrupts) to perform the required duty when some event occurs. Monitoring and controlling the state of the battery supply is another of their critical functions. When the battery tput voltage is lower than required, the battery is discharged and needs to be recharged. Similarly, when the battery output is higher than required, a flag can be asserted when the battery is completely charged and needs no further charging. It is also essential to monitor the battery case temperature, since this offers valuable insight into the loading conditions, ambient temperature, or the presence of a fault.

An analog-to-digital converter (ADC) or comparator with window function provides a simple solution to monitor battery voltage and temperature. There are also sophisticated battery monitors and fuel gauges designed specifically for this function. But a careful trade-off must be made, keeping power, speed, accuracy, cost and form factor (space constraints) in mind. Different systems can require different priorities from the aforementioned list, affecting the overall system design. Before examining battery voltage monitoring and temperature monitoring using comparators, this application note first covers some basic, yet important, information about batteries.

Restrictions of Secondary Batteries

Secondary or rechargeable batteries differ in their chemical composition and structure from one to another. These differences, in turn, dictate the specific power (maximum current delivered to load), lifespan, and thermal stability of battery cells. There are also trade-offs to consider: the higher the specific power, the lower the safety rating, life span, cost, and vice versa.

Secondary batteries wear out, possess a charge-discharge lifecycle, and come with certain restrictions, including:

1. The amount of current they can provide for a specified range of output voltage over time
2. The amount of current they can take in (during charging)
3. Maximum safety voltage (the voltage level to which they can be charged)
4. Minimum safety voltage (the voltage level to which they can be used)
5. The amount of heat or cold they can withstand

Each of these restrictions affects the battery's lifespan. Not adhering to these conditions can cause the battery to wear out sooner or even flare up. The above-mentioned ratings change based on the battery capacity, which is directly proportional to the form factor or the size.

Secondary Batteries for Portable Electronics

Table 1 shows the typical characteristics of the most common secondary/rechargeable single-cell battery types.

- Maximum safety operating voltage is the voltage termed as fully charged and ready. Attempting to charge more is possible, but comes with the risk (sometimes catastrophic) of reducing lifespan.
- Minimum cutoff or disconnect voltage is the voltage assuming the cell has drained. Taking the battery voltage below the cutoff point shortens battery lifespan.
- Cycle lifetime and lifespan are different. Each time a battery goes through a cycle charge to discharge is considered a cycle lifetime. The more often you charge/discharge your smartphones, the shorter the lifespan you can expect.

Table 1. Typical Characteristics of Secondary/Rechargeable Single-Cell Batteries

Battery Type	Maximum Safety Operating Voltage	Discharge Voltage or Minimum Cutoff Voltage	Nominal Voltage (VBAT)	Average Cycle Lifetime	Average Self-Discharge (% Discharge/Month)
Lithium-ion					
Lithium cobalt oxide ($LiCoO_2$)	4.2	2.5	3.6	750	1 to 2
Lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$)	4.2	2.5	3.6	1500	1 to 2
Lithium iron phosphate ($LiFePO_4$)	3.6	2.0	3.2	1500	1 to 2
Lithium-ion polymer					
Lithium polymer	4.2	2.0	3.6	400	1 to 2
Nickel					
Nickel cadmium*	1.45	0.9	1.2	2000	10 to 15
Nickel metal hydride*	1.3	1	1.2	1500	10 to 15

**Three single cells are used for a typical 3.6V battery output.*

As Table 1 notes, lithium polymers can have low cycle lifetime, but their form factor, weight, and maximum-minimum voltage rating (charge density) offer more advantages. In portable electronics, nickel-alloy combination and lithium-ion combination batteries are commonly used. These types of applications rarely use lead-acid batteries, as they are usually too heavy (energy-to-weight ratio). Repetitive full-discharge cycles place extreme stress on the chemical properties of these batteries, reducing their lifetime. While they are among the cheapest batteries available, lead acid and nickel cadmium types are harmful to the environment and are mainly used in stand-alone/backup power supplies.

Self-Discharging and Power Budgeting

Self-discharge refers to the reduction of battery capacity by internal unwanted chemical reactions. This is why shelf life is reduced, even when the battery is not used. Consider a lithium-ion polymer battery with a rating of 1000mAh. The capacity rate, or C-rate, designates the rate at which the battery is discharged to its maximum capacity. 1C means that the battery can provide 1000mA for one hour until it is completely discharged. Similarly, 0.5C means that the battery can provide 500mA of current for two hours until it is discharged.

A very reasonable approximation to discharge a battery of 1000mAh capacity over a month is approximately

$$\frac{1}{(24 \times 30)\ \text{hours}} = 0.001388\text{C}$$

or

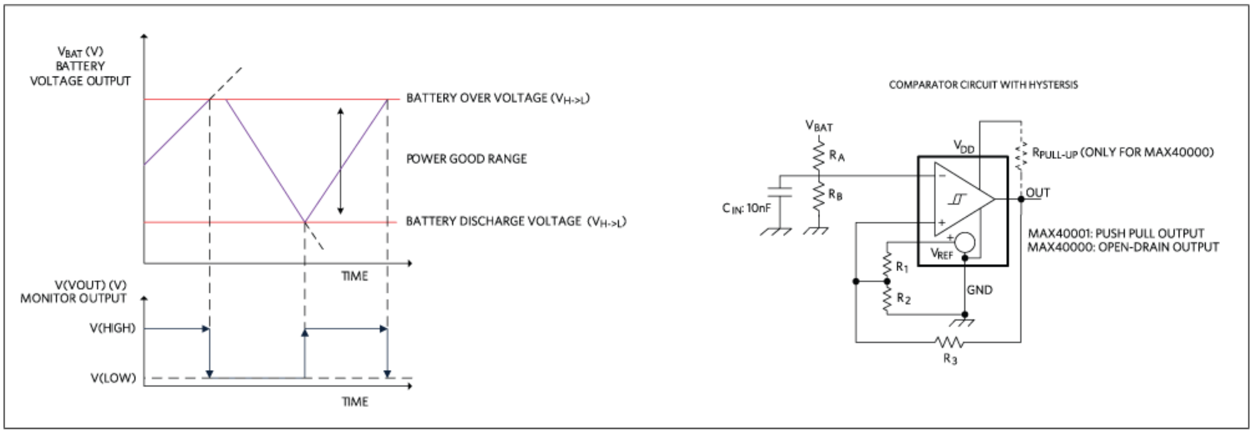
$$\frac{1000\text{m}}{(24 \times 30)\ \text{hours}} = 1.388\text{mA}$$

discharge current.

Therefore, a self-discharge of 1% capacity per month (from Table 1) is equivalent to 1% of discharge current of 0.001388C, which is (1% of 1000mAh/720 hours) Â 14μA.

If the application circuit consumes less than the discharge current, the battery is limited by the shelf life, not the current consumed by the application circuit. The MAX40000/MAX40001 (1.11mm x 0.76mm footprint) and MAX40003/MAX40004 (0.73mm x 0.73mm footprint) ultra-low-power comparators have an internal reference featuring under 1μA quiescent current. The lower quiescent current is comparable to current typical self-discharge rate of the battery cells, making these devices the prime choice for power monitoring when power dissipation requirements are stringent.

Battery State with Micro-Power Comparator **Figure 1** shows a simple comparator monitoring the battery state. The comparator output voltage transitions from high to low in case of a fully charged voltage and from low to high to convey a fully discharged battery voltage. To produce the correct output states, the circuit is implemented with external hysteresis and selected thresholds.



Input/Battery Voltage	Output Transition
V_{BAT} $V_{H->L}$	High to Low

V_{BAT} $V_{L->H}$	Low to High

Figure 1. Comparator with hysteresis function to indicate "charged" and "discharged" battery voltages.

The comparators shown are tiny-footprint devices with internal reference, consuming 900nA of quiescent current. Implementing the circuit with large-value resistors ensures that the overall operating current is comparable to the typical self-discharge rate of the battery cells. The circuit operates from a supply voltage as low as 1.7V and requires less than 2µA of supply current. This ensures that, even for a battery with a minimal remaining charge, the circuit still produces the correct output state.

Table 2 provides typical component values to realize trip points for V_{BAT} ($V_{H->L}$ and $V_{L->H}$) battery monitoring.

Table 2. Typical Component Values for Battery Monitoring (V_{DD} = V_{PULLUP}= 1.8V, V_{SS} = GND)

Battery Type	Lithium Cobalt Oxide/Lithium Nickel Manganese Cobalt	Lithium Polymer	Lithium Iron Phosphate	Nickel Cadmium*/Nickel Metal Hydride*
Trip Points	$V_{H->L}$ = 4.0V $V_{L->H}$ = 2.64V	$V_{H->L}$ = 4.0V $V_{L->H}$ = 3.2V	$V_{H->L}$ = 3.4V $V_{L->H}$ = 2.2V	$V_{H->L}$ = 3.4V $V_{L->H}$ = 3.0V
Push-Pull Output Option (MAX40000)	RA = 6.02MΩ	RA = 3.7MΩ	RA = 2MΩ	RA = 2MΩ
	RB = 1MΩ	RB = 1MΩ	RA = 4.6MΩ	RB = 1MΩ
	R1 = 5.4MΩ	R1 = 5.4MΩ	R1 = 5.4MΩ	R1 = 1.54MΩ
	R2 = 2.7MΩ	R2 = 3.01MΩ	R2 = 3.01MΩ	R2 = 10MΩ
	R3 = 15.4MΩ	R3 = 15.4MΩ	R3 = 15.4MΩ	R3 = 20MΩ
Open-Drain Output Option (MAX40001)	R_{PULLUP} = 2.2MΩ	R_{PULLUP} = 2.2MΩ	R_{PULLUP} = 2.2MΩ	R_{PULLUP} = 2.2MΩ

**Three single cells are used for a typical 3.6V battery output.*

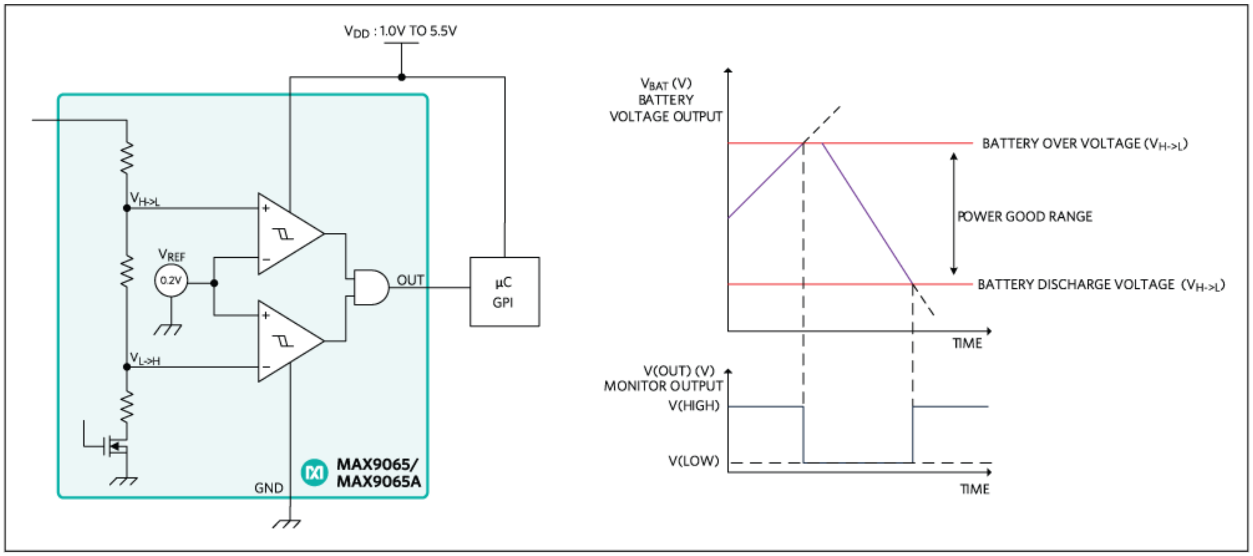
Table 2 provides typical characteristic component values to realize the battery state monitoring application. Compared to Table 1, the determined threshold value provides a narrower band of hysteresis, which allows more cushion for component tolerances and variations. The entire circuit provides ±1% accuracy on trip points with 0.5% tolerance resistors for the circuit shown in Figure 1. For better accuracy performance, tighter tolerance resistors an be used.

Li-Ion/Ni-Cd Battery Voltage Monitoring

The MAX9065 is a single-chip solution to monitor battery voltage. It features two internal comparators with internal reference and resistor string to form a window comparator. All it requires is to have the battery output be connected at the IN and VCC input. Additionally, the device can perform as low as 1.0V supply input. This enables the application to work even if the battery is past discharge voltage. The device comes in two types: MAX9065E and MAX9065A. The MAX9065E monitors single-cell Li-ion cells, and the MAX9065A provides Ni-cd battery monitoring.

Figure 2 shows the dual comparator approach solving Li-ion and Ni-Cd battery monitoring. The appropriate trip points that are set internally reduce component count and area with ±1% accuracy.

The application circuit shown in Figure 2 consumes less than 1µA and can perform with as little as 1.0V supply input, so the application can work even if the battery is past discharge voltage.



MAX9065E Operation	
Input/Battery Voltage	**Output**
V_{BAT} > 4.2V	Low
3.0 < V_{BAT} < 4.2V	High
V_{BAT} < 3.0V	Low

MAX9065A Operation	
Input/BatteryVoltage	**Output**
V_{BAT} >1.2V	Low
0.6 < V_{BAT} < 1.2V	High
V_{BAT} < 0.6V	Low

Figure 2. Li-ion, Ni-Cd battery monitoring using MAX9065.

Temperature Monitor

Excessively high temperature often signals a problem, and can permanently damage an electronic device. There are various potential causes, including high ambient temperature, excessive power dissipation, or incorrect battery charging/discharging. Cause aside, anytime the temperature is too high, the system should be shut down for protection.

Figure 3 shows a simple circuit using the MAX40004 th at employs a negative temperature coefficient (NTC) thermistor to monitor the device temperature. It is usually placed close to the battery pack to ensure that its ambient temperature is very close to that of the battery.

An NTC thermistor's resistance is inversely proportional to temperature. For example, a 100kΩ nominal thermistor with 0.5% tolerance at +25°C is 100kΩ, but its corresponding resistance would be approximately 8.8kΩ at +85C. R1 is 1.08MΩ and R2 is 120kΩ. At +85°C, the voltage at the comparator's noninverting input is just enough to trip the output to low. The device's internal hysteresis provides a 15°C hysteresis to reduce sensitivity to noise.

The comparator shown in Figure 3 is available in a space-saving 4-bump WLP and requires less than 500nA of quiescent supply current. The application consumes under 2μA of total supply current.

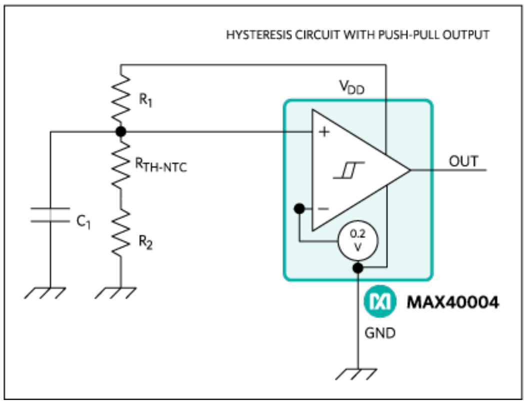


Figure 3. Temperature monitoring using MAX40004.

Summary

Requiring little or no power budgeting, battery monitoring and protection circuits can offer a critical block in mobile and wearable electronic devices.

Other Resources/References

1. BatteryUniversity.com
2. Batteryspace.com
3. Application note 3616, "Adding Extra Hysteresis to Comparators"

Related Parts		
MAX4000	2.5GHz 45dB RF-Detecting Controllers	Free Samples
MAX40001	1.7V, nanoPower Comparators with Built-in Reference	Free Samples
MAX40002	nanoPower 4-Bump Comparator in Ultra-Tiny 0.73mm x 0.73mm WLP/SOT23 Packages	Free Samples
MAX40003	nanoPower 4-Bump Comparator in Ultra-Tiny 0.73mm x 0.73mm WLP/SOT23 Packages	Free Samples
MAX40004	nanoPower 4-Bump Comparator in Ultra-Tiny 0.73mm x 0.73mm WLP/SOT23 Packages	Free Samples
MAX40005	nanoPower 4-Bump Comparator in Ultra-Tiny 0.73mm x 0.73mm WLP/SOT23 Packages	Free Samples
MAX9065	Ultra-Small, nanoPower, Window Comparator in 4 UCSP and 5 SOT23	Free Samples

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