

# Smart batteries

A. K. Shukla\* and B. Hariprakash

*At present, smart batteries are primarily required for the laptop computers, which must squeeze more performance into smaller packages while increasing battery life at the same time. To achieve these goals, the designer must incorporate new methods of optimizing system power consumption and available battery capacity. As battery-management techniques mature and become more common, application regime of smart batteries will extend beyond the laptop computers to other portable devices, in medical electronics, portable test equipment and other battery-powered systems.*

A battery is a device, which enables the energy liberated in a chemical reaction to be converted directly into electricity. Batteries are primarily used (a) as portable sources of electric power for mobile phones, for the starting, lighting and ignition in vehicles with internal combustion engines, electric vehicles and other similar applications, and (b) in the industrial market, such as emergency power supplies for public safety and biomedical applications, aviation, defence, load levelling or in conjunction with certain renewable energy sources, namely solar, wave or wind power, for energy storage and its retrieval on demand. Beginning with the invention of lead-acid battery by Gaston Planté in 1859, a variety of battery chemistries have been developed and marketed. Although each of these battery systems offers distinct advantages, none provides a fully satisfactory solution. However, with today's increased selection, better choices can be applied to suit a specific user application to best avail the effective battery capacity window (Figure 1)<sup>1</sup>.

The battery most commonly known to us is the dry cell, which we use in our radio sets or torches. These are purchased in their charged state and discharged through use, and then discarded. Such cells are known as primary cells. The growing need for recycling resources requires that the discharged battery should be reusable a large number of times. This requires secondary (or rechargeable) batteries with long charge/discharge cycle lives.

Currently, three types of rechargeable batteries, namely nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH) and lithium-ion (Li-ion), are being used as portable power sources. Ni-Cd batteries represent the best possible balance between specific energy, specific power, cycle-life and reliability. But, Ni-Cd cells suffer from the memory effect, a phenomenon that burdens the user with having to at least occasionally follow a time-consuming recharging regime in order to maintain their rated capacity. Besides,

cadmium is an awful poison that can contaminate the environment. The unpopularity of cadmium has encouraged the development of Ni-MH batteries. Ni-MH batteries are not only cadmium-free, but can also store more energy than comparably sized Ni-Cd units. On the downside, Ni-MH batteries deliver less power and have a faster self-discharge rate. Therefore, attempts have been focused on lithium, which is the lightest and most reactive of metals, for batteries. One of the most promising lithium secondary batteries is the Li-ion battery, which is the new standard for portable power.

An ordinary or 'dumb' battery has the inherent problem of not being able to display the amount of reserve energy it holds. Since the weight, colour and size of a battery do not provide any indication of its state-of-charge (SOC; the fraction usually expressed as a percentage of the full capacity of a battery that is still available for further discharge) and state-of-health (SOH; a measurement that reflects the state-of-health of a battery, taking into account its charge acceptance, internal resistance, voltage and self-discharge), the user is at the mercy of the battery while pulling a freshly-charged battery from the charger. Therefore, an increasing number of rechargeable batteries are now being made 'smart', in order to ensure effective communication between the battery and the host device.

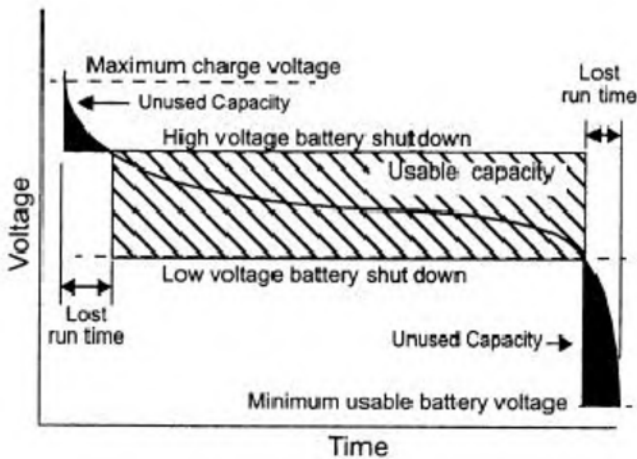
Various reasons for adopting smart batteries are<sup>2</sup>: (a) to prevent unexpected loss of power and shutdowns, (b) enable longer battery run-times, (c) enable precise indication of SOC of the battery, run-time remaining, time to full charge, etc., (d) provide a cost-effective advanced warning system by closely monitoring SOH of the battery due to effects of environment, age and wear, (e) enable battery performance trending and diagnostics, (f) assure safe, battery-controlled smart charging to get a full charge every time and minimize battery abuse due to overcharging, (g) improve cycle-life, (h) enable effective power-management systems that take advantage of accurate information supplied by the battery, (i) design in battery chemistry independence and (j) permit remote battery monitoring.

The authors are in the Solid State and Structural Chemistry Unit, Indian Institute of Science, Bangalore 560 012, India.

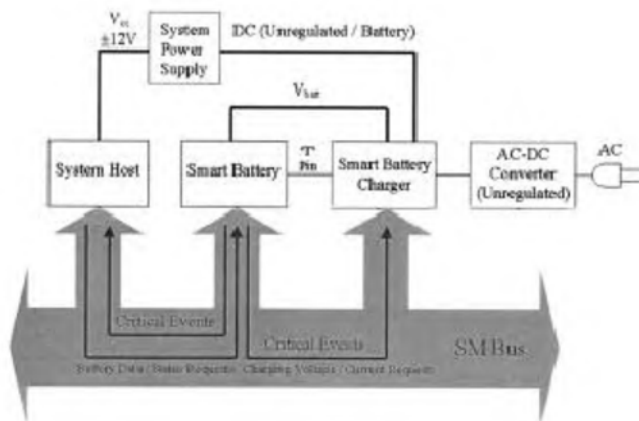
\*For correspondence. (e-mail: shukla@sscu.iisc.ernet.in)

**Smart battery system**

A standard method of communication developed by battery manufacturers and microprocessor companies is the smart battery system (SBS) based on the system management bus (SM Bus)<sup>3</sup>. The SM Bus provides the physical medium based on the inter-integrated circuit bus (I<sup>2</sup>C Bus, a two-wire open-collector multi-master/multi-drop serial bus that uses clock and data signals to communicate with up to 127 devices on a single bus) and command protocols that support the transfer of information among smart battery system components<sup>4</sup>. Typical schematic of a smart battery system<sup>5</sup> is shown in Figure 2. Equipped with a microchip, these smart batteries communicate with the charger and user alike, to provide statistical information pertaining to their chemistry, charge algorithm, protection against overcharging, under discharge, short-circuiting and SOC/SOH indication<sup>6</sup>. The smart battery communicates with other devices such as the SM Bus host and the smart battery charger via two separate communication interfaces<sup>7</sup>. The first uses the



**Figure 1.** Schematic battery discharge curve depicting its effective capacity window.



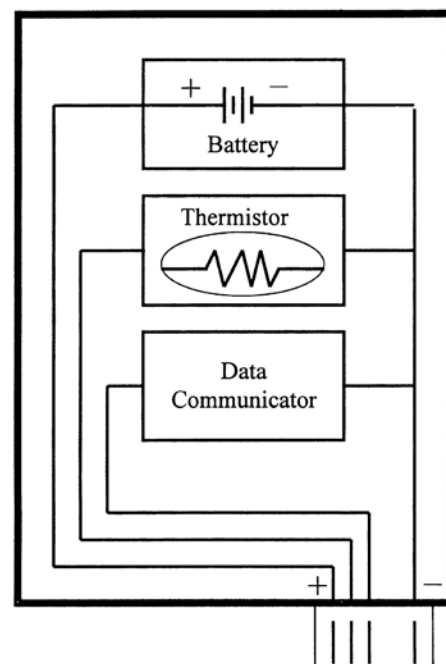
**Figure 2.** Schematic description of a typical smart battery system.

SM Bus CLOCK and DATA lines, and is the primary communication channel between the smart battery and other SM Bus devices. The smart battery will provide data when requested, send charging information to the smart battery charger, and broadcast critical alarm information when parameters (measured or calculated) exceed predetermined limits within the particular smart battery. The other required communication interface is the secondary signalling mechanism or ‘safety signal’ on a smart battery pack connector. This is a variable resistance output from the smart battery which indicates when charging is desired. It acts as an alternate signalling method if the SM Bus becomes inoperable. It is primarily used by the smart battery charger to confirm correct charging.

Smart battery architectures with SOC read-out are categorized as the single-wire system, the two-wire system and the SM Bus architectures. Most two-wire systems are based on the SM Bus protocols. The single-wire bus and SM Bus protocols are briefly discussed in the following sections.

**Single-wire bus smart battery architecture**

The single-wire system of the ‘smart’ battery uses only one wire for data communication. A battery equipped with the single-wire system uses only three wires separately connecting the positive and negative terminals of the battery and the data terminal. For safety reasons, most battery manufacturers run an additional wire for temperature sensing as shown in Figure 3. Besides, rather than supplying the clock signal externally, the battery includes an



**Figure 3.** Schematic description of single-wire bus smart battery architecture.

embedded clock generator. The modern single-wire system stores battery-specific data and tracks battery parameters, including temperature, voltage, current and remaining charge. Because of its simplicity and relatively low hardware cost, the single-wire bus smart battery architecture enjoys a broad market acceptance in mobile phones, two-way radars and camcorders. However, most single-wire systems do not have a common form factor and hence are not compatible with the universal charger concept [in electric motor terminology, a form factor is the amount of rectified current emitted from a direct current (DC) power source and is expressed as a ratio of the root-mean square (rms) value of the current to the average (av) current, i.e.  $I_{rms}/I_{av}$ . If the form factor differs much from pure non-pulsating DC (a value of 1.0), it indicates the possibility that motor and brush life will be shorter]. Furthermore, the single-wire bus battery architecture allows battery SOH measurements only when the host uses a specified battery pack. Such a fixed host–battery relationship is feasible with notebook computers, mobile phones and video cameras, provided the appropriate original equipment manufacturer (OEM, a company that uses product components from other companies to build a product that it sells under its own company name and brand) battery is used. Any discrepancy in the battery type from the original type will make the system unreliable or will provide false data.

### SM Bus smart battery architecture

The SM Bus smart battery architecture is based on a two-wire system using a standardized communications protocol (Figure 4). Unlike the single-wire bus smart battery architecture, this system provides standardized SOC and SOH measurements. The SM Bus smart battery architecture includes both the batteries containing the charging unit within the pack as well as the batteries with external charger. The SM Bus host is powered by a smart battery. It requests information from the battery and then uses it in the ‘power management scheme’ of the system and/or provides user information about the state and capabilities of the battery. The SM Bus host will also receive critical events from the smart battery when it detects a problem. In addition to the alarms sent to the smart battery charger, it receives alarms for end-of-discharge, remaining capacity and remaining run time below the user-set threshold value. Standardization of communication through SM Bus was further augmented by a set of data protocols for a smart battery, smart battery charger, system host and other SM Bus devices. The resulting set of standards has been adopted by the industry and is now called the ‘smart battery system specifications’. This group of specifications details the methods of communication, protocols, and the data interfaces among various power management-related devices used in portable computing products. The downsides of the SM Bus smart battery systems are that these are costly and require serious maintenance.

### Smart battery charger

The smart battery charger is a charging circuit that provides the smart battery with charging current and charging voltage to match the expected requirements of the smart battery. The battery charger periodically communicates with the smart battery and adjusts its charging characteristics in response to information provided by the smart battery. This allows the battery to control its own charge cycle. Optionally, the smart battery charger may not allow the smart battery to supply power to the rest of the system when the smart battery is fully charged and the system is connected to AC power, thus prolonging the life of the battery. The smart battery charger will also receive critical events from the smart battery when it detects a problem. These include alarms for charging or temperature conditions when they exceed the limits set within the particular smart battery. A safety signal using a resistance output from the smart battery is also used as a gating mechanism for battery charging.

### Electronic energy management and display

Electronic circuitry is used to maximize battery service life by terminating the discharge as close as possible to the specified cut-off voltage. Terminating the discharge at too high a voltage will result in loss of a significant amount of battery capacity. By contrast, terminating it at too low an end-voltage discharges the battery beyond its

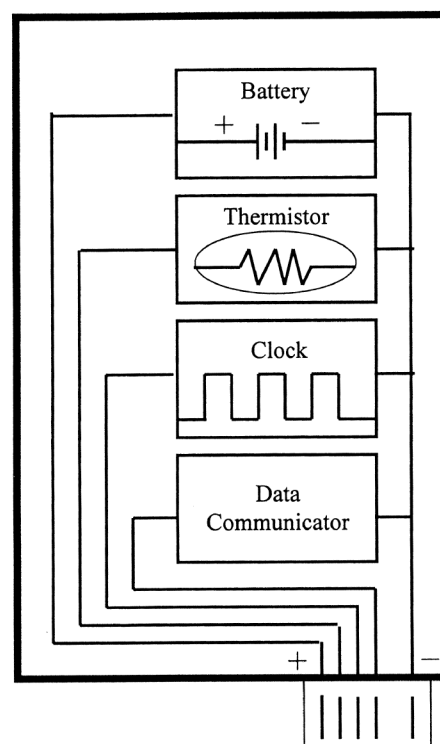
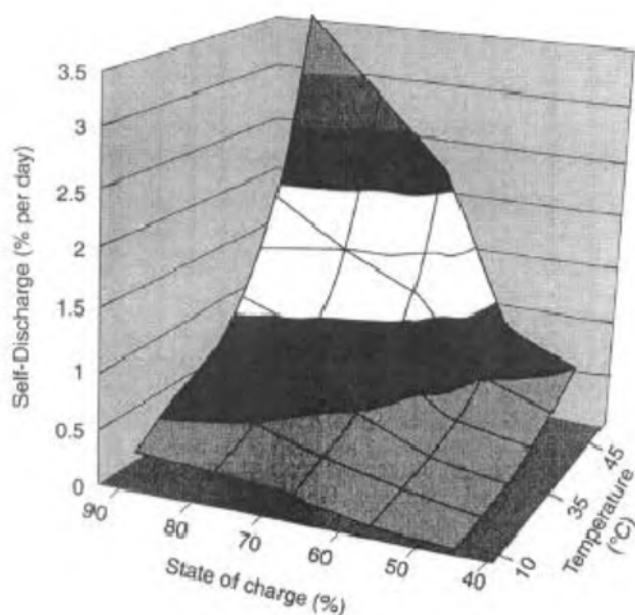


Figure 4. Schematic description of SM Bus smart battery architecture.



**Figure 5.** Self-discharge rate vs state-of-charge and temperature for a sealed nickel–metal hydride battery.

safe cut-off and could cause permanent damage to the battery. A typical battery capacity window is shown in Figure 1. Similarly, on charge, accurate control, as discussed above, will enable a maximum charge under safe conditions without damage to the battery.

The smart battery electronics must continuously monitor the internal cell voltage, temperature and the charge and discharge currents for a correct representation of the capacity, run-time, and SOC of the smart battery. The smart battery electronics must also know how the battery will perform under various conditions such as temperature, charge and discharge rates, etc.<sup>8</sup>

By proper placement of a thermistor within the battery pack, a measurement of the temperature of the battery is available and  $T_{\max}$ ,  $T_{\min}$ ,  $\Delta T/\Delta T$  or other such parameters can be established for charge control, along with  $-\Delta V$  information from the microprocessor. In addition, the battery temperature is sensed during discharge to control the discharge, e.g. loads are turned off to lower the battery temperature if excessively high temperatures are reached during the discharge. Discharge control is also provided to control such conditions as discharge rate, end-voltage, cell equalization and temperature management. Individual cells as well as the entire battery pack are monitored to maintain cell balance during cycling<sup>9</sup>.

SOC indicators are commonly known as ‘gas gauges’, and provide estimates for the remaining battery capacity by factoring in variables such as the discharge rate and time, temperature, self-discharge, charge rate and duration. The remaining capacity is normally displayed by a

sequence of illuminated LEDs or as a direct output to the device being powered. Data are collected during the life of the battery to update the database and, as required, changes are made to maintain optimum performance.

Early smart battery electronics used simple linear models for estimating battery performance characteristics which severely limited the accuracy in predicting the performance of the battery, since it is not linear with respect to current drain and temperature. Similarly, self-discharge has a complex relationship and is influenced by temperature, time, state-of-charge and the discharge load at which it is measured. Figure 5 shows the nonlinear relationship of the rate of self-discharge with temperature and time for a metal-hydride battery<sup>10</sup>. It is seen that the self-discharge rate of the metal-hydride battery at SOC = 0.9 at 45°C is 3.5% per day. Besides, the performance of even the batteries using the same chemistry varies with design, size, manufacturer, age, etc. An appropriate algorithm will account for these relationships to predict the remaining service life and assuring safe operation of the battery.

## Summary

Smart batteries offer promise for substantial improvements in battery technologies. However, smart batteries need tight-tolerance in their design for safety, maximum available capacity and least abuse. Most smart battery applications today are limited to portable electronic equipment, but the need to develop larger ‘smart’ batteries for use in electric vehicles, robots, forklifts and automotives will emerge soon.

1. Martinez, C., Drori, Y. and Ciancio, J., Smart Batteries and the Xircor X3100, XICOR Application Note, AN127, October 1999.
2. <http://www.powersmart.com>
3. <http://www.sbs-forum.org>
4. Friel, D., Battery Centric Charging: Benefits and Applications, Portable by Design and Wireless Symposium, PowerSmart Inc., February 1999.
5. Friel, D., The importance of Full Smart Battery Data (SB Data) Specification Implementation, PowerSmart Inc., August 1998.
6. Buchmann, I., Batteries in a portable world. <http://www.buchmann.ca>
7. Friel, D. and Mattera, M., SBS Smart Battery Interface Guidelines, Portable and Wireless, 1998.
8. Friel, D., Smart Batteries Simplify Portable Power System Design, Conference Proceedings, IIC-Taipei, June 1999.
9. Linden, D. and Reddy, T. B. (eds), *Hand Book of Batteries*, McGraw-Hill, NY, 2002, 3rd edn.
10. Norman Allen, J., The Payoff in Smart Battery Electronics, *Battery Power Products and Technology*, July 2000.

ACKNOWLEDGEMENT. We thank the referee for his valuable comments.

Received 3 April 2003; revised accepted 1 May 2003