Designing a New Generalized Battery Management System

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***Abstract*—Battery management systems (BMSs) are used in many battery-operated industrial and commercial systems to make the battery operation more efficient and the estimation of battery state nondestructive. The existing BMS techniques are examined in this paper and a new design methodology for a generalized reliable BMS is proposed. The main advantage of the proposed BMS compared to the existing systems is that it provides a fault-tolerant capability and battery protection. The proposed BMS consists of a number of smart battery modules (SBMs) each of which provides battery equalization, monitoring, and battery protection to a string of battery cells. An evaluation SBM was developed and tested in the laboratory and experimental results verify the theoretical expectations.**

***Index Terms*—Batteries, error analysis, fault diagnosis, fault tolerance, protection, reliability.**

I. Introduction

THERE ARE MANY applications where batteries are the primary option for electric energy storage. Electric road vehicles (EVs), uninterruptible power supplies (UPSs), renewable energy systems, and cordless electric power tools are examples of such applications. Battery management is relatively simple in low-power applications and, thus, a great number of integrated solutions are available. However, in high-power systems, long battery strings of high-capacity batteries are used and the probability of problem occurrence is increased as well as the repair costs. The low ratio of cell voltage to string voltage and the particularity of each battery string make battery management difficult in these systems. In spite of this, a number of sophisticated battery management system (BMS) solutions have been proposed [1]–[7] and although most of them are microcontroller-based solutions, none of them provides:

- advanced fault tolerance;
- maximization of the delivered battery energy;
- battery protection.

All of the proposed solutions are mainly monitoring systems, cell or battery based, which can estimate the battery state and stop suitably the battery charging, in order to prevent overcharge and protect the battery from life shortage. Some of them can provide charge equalization, using topologies that allow limited discharge equalization also [8]–[10]. If fault tolerance is provided, this is accomplished by using two separate battery strings. This method has several disadvantages, such as a complicated battery circuit and double number of monitored cells.

The need of a generalized design method, which can be applied in every case of battery management requirements and which provides a state-of-the-art BMS, led to the development of the proposed methodology described in this paper. An experimental model of a typical smart battery module (SBM) was developed and tested in order to verify the implementation problems and examine the real system behavior. The proposed methodology assumes a cell-based BMS that manages batteries that consist of a number of cells and allow access to cell interconnection.

A. BMS Design Considerations

The requirement for a state-of-the-art BMS design and the experience obtained from an experimental SBM and existing BMS studies [11], [12], lead to the conclusion that the design considerations should be extended in order to include:

- full battery power equalization capability;
- battery cell disconnection capability;
- operation in the noisy environment of high-power converters that may operate within the SBM.

Each one of these new BMS considerations will be examined below, in order to determine the methods that can be used and the application area of each method.

Full Battery Power Equalization Capability: A BMS must have bidirectional equalization capability, which will assure that all battery cells have uniform charging and that the energy delivered by the battery string is maximized. Full battery power equalization also provides fault tolerance capability by maintaining the terminal voltage of a disconnected battery cell under load conditions. Two methods have been described to achieve this. According to the first method [13], a separate bidirectional converter is placed in parallel with each battery cell. In the second method [14], a multiterminal full-wave bidirectional push–pull dc/dc converter is formed around a single multiwinding transformer. The converter is used to maintain the cell voltages equal. The first method may give better results, since each converter uses its own negative feedback, which provides strictly controlled internal resistance, resulting to a better output voltage stability against load current variations, but it cannot be used in a generalized SBM. The

Manuscript received February 15, 2002; revised October 22, 2002. Abstract published on the Internet July 9, 2003.

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Digital Object Identifier 10.1109/TIE.2003.817706

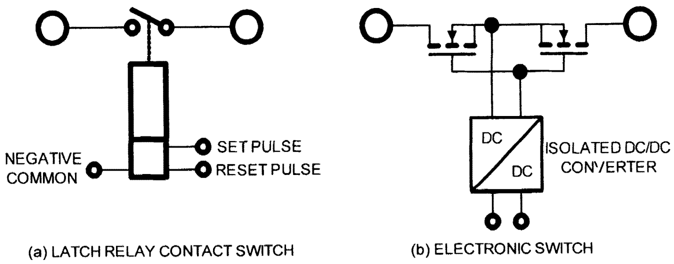

Fig. 1. Comparison between (a) a latch relay contact switch and (b) an electronic switch.

problem is that the second terminal of each separate converter has to be connected to the total string voltage, which may be different for each battery string. The second method is simpler and can easily be implemented in a generalized SBM, because the coupling voltage of the modules is produced from an extra module coupling winding of the multiwinding transformer, and thus it is independent of the total battery string voltage.

Battery Cell Disconnection Capability: The BMS has inherently a very accurate "battery condition monitor" [15]. Battery protection must be a primary function of any BMS. Since battery cells are integral parts of batteries, it is impossible to disconnect a single cell when it is defective. However, when this occurs, the defective cell battery block can be isolated and since its equalizer can maintain the isolated battery block voltage, the operation of the battery string will not be interrupted. The best way to isolate a battery block from the point of view of energy efficiency and safety is by using latch relays (Fig. 1).

If electronic switches were used, power losses should result from (a) the continuous operation of the isolated dc/dc converter as long as the switch is in the "ON" state and (b) because the electronic switch "ON" state resistance ($2 \cdot R_{DSON}$) is higher than that of the contact switch. Furthermore, when the contact switch is in the "OFF" state, usually, it can withstand higher voltage.

Operation in Noisy Environments: A high-power equalization converter is utilized in the SBM and, unlike the existing BMS techniques, the proposed SBM has power and signal stages on the same printed circuit board. The printed circuit board must be designed in such a way that the signal circuitry will not be affected by ground noise, electromagnetic interference (EMI) and radio frequency interference (RFI), because the measurements accuracy of battery cell voltages must be in the order of few millivolts or a few tenths of millivolts, indicating that a battery cell monitor is more sensitive in ground noise than other monitors of power electronics systems, such as UPSs, etc. To achieve this, all the analog communications paths between the microcontroller and the sensors must be balanced in order to emulate twisted-pair conductors and avoid ground noise effects. Multilayer printed circuit boards may act even better by shielding the analog signal paths and allowing more efficient high current paths.

II. General BMS Operation Concepts

A BMS has to be "cell based" in order to be effective. Usually the cells are parts of larger battery blocks with nominal voltage of 6 or 12 V. Access to the battery cell terminals can be obtained by making holes at correct points on the cover [2]. On the other hand, according to the proposed methodology, it is not required to cut the battery interconnections between the cells for the measurement of each cell current. The proposed methodology can be modified to a "battery-based" structure, where a SBM manages a set of batteries and not cells of a battery, but in this case the advantage of maximization of the battery string delivered energy is sacrificed. Most typical battery applications use voltages that are multiples of 12 V [16], which is a convenient voltage for the operation of the SBM. This voltage is produced by six lead-acid cells or by ten alkaline-electrolyte cells. A universal SBM can be designed for both types of cells, capable of using either six or ten cells. But, it is impractical to use a universal SBM operating only with lead acid cells, due to the extra cost of the redundant power and sensor circuitry. Thus, a specific SBM design is recommended, depending on cell chemistry. The 12-V SBM is the base for any typical application and will be repeated as many times, as the application requires. In this paper, a lead-acid SBM is considered.

Equalization in a BMS needs a second current path along the battery string. This path is used for the current tradeoff of the cells parallel current paths.[1] The communication and other system wiring can go next to this path and, thus, the minimization of the number of conductors may not be a primary design option in such a type of BMS.

A fault-tolerant BMS is more flexible, if all its SBMs are similar and a special master module is responsible for communication timing, system control and external requests. Otherwise, faults may not be detected on time. The number of measurements handled by such a type of SBM is about twice as many handled by a normal battery measurement unit, while the speed requirements are also increased. The master module can measure the string voltage and current and thus prevent any malfunctions caused by communication delays of SBMs. The computation load should be evenly distributed to the microcontrollers in order to avoid computation overload in the master module and to minimize the traffic to the SBM communication network. Thus, each microcontroller can process its input data and pass only the necessary parameters to the master module. Measurements can be exchanged between modules, but only for test and calibration purposes.

Fig. 2 shows a block diagram of the typical BMS topology that includes a battery charger and the final stages of the power sources, which are not counted as parts of the BMS, but show clearly the various charging situations that a BMS has to cope with.

Different power sources can be used to supply energy to the charger, such as:

- inductive charging, as in the EV and hybrid EV (HEV);
- renewable energy sources (photovoltaics and/or wind generators); usually, these sources are controlled by max-

[1]During the equalization phase of a series string of battery cells, all cells are under the same voltage level. In order for this to happen, the cells absorb different currents and this can occur only if there exists a parallel path with each cell. Since these parallel currents represent power, it is convenient to convert this power and return it through another path to the total battery charging current.

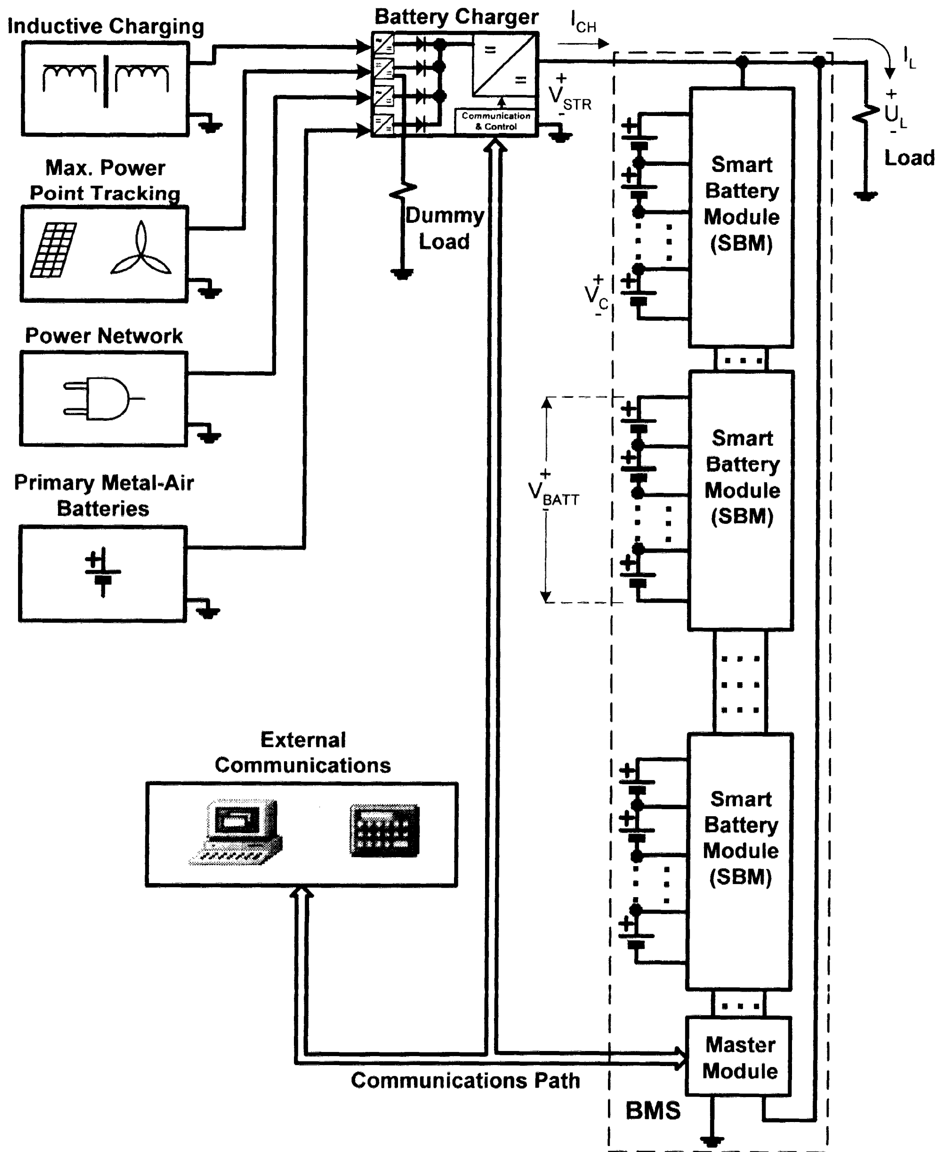

Fig. 2. Block diagram of a typical BMS topology.

imum power point tracking (MPPT) units and a dummy load is used to dissipated the excessive power;
- power network as in the UPS case can supply the charger;
- primary metal-air batteries, in some special cases of EVs are used as high energy density deposit, charging the conventional batteries capable to provide high current required for the vehicle operation.

The master module contains a microcontroller and measures the voltage and the current of the battery string. It controls the charger voltage and the main operation of the BMS. The master module manages all communications, both inside the BMS and outside. A computer or an LCD display and a keyboard, communicating with the master module, can be used to monitor BMS operational data or externally control the BMS operation.

Each SBM is consisted of a microcontroller, the necessary circuitry to monitor the battery behavior, an equalization converter and adequate number of switches, that are capable to totally disconnect the battery from the battery string. All the equalization converters are coupled and the operation of all the SBMs is controlled and supervised by the master module.

The battery string current equals the difference $I_{CH} - I_L$. Charging occurs only while $I_{CH} > I_L$.

For each specific application of the BMS, the program of the master module microcontroller has to take into account the characteristics of the power source in order to avoid, either memory effects in alkaline electrolyte cells, or long periods in deep discharge state for lead acid batteries.

III. Proposed SBM

A block diagram of the proposed SBM is shown in Fig. 3. The battery cells are connected through latch-relay switches to the SBM. This topology allows battery block disconnection, in case of malfunction. If this happens, the equalizer retains the battery voltage with energy provided through the current tradeoff path by the good battery cells.

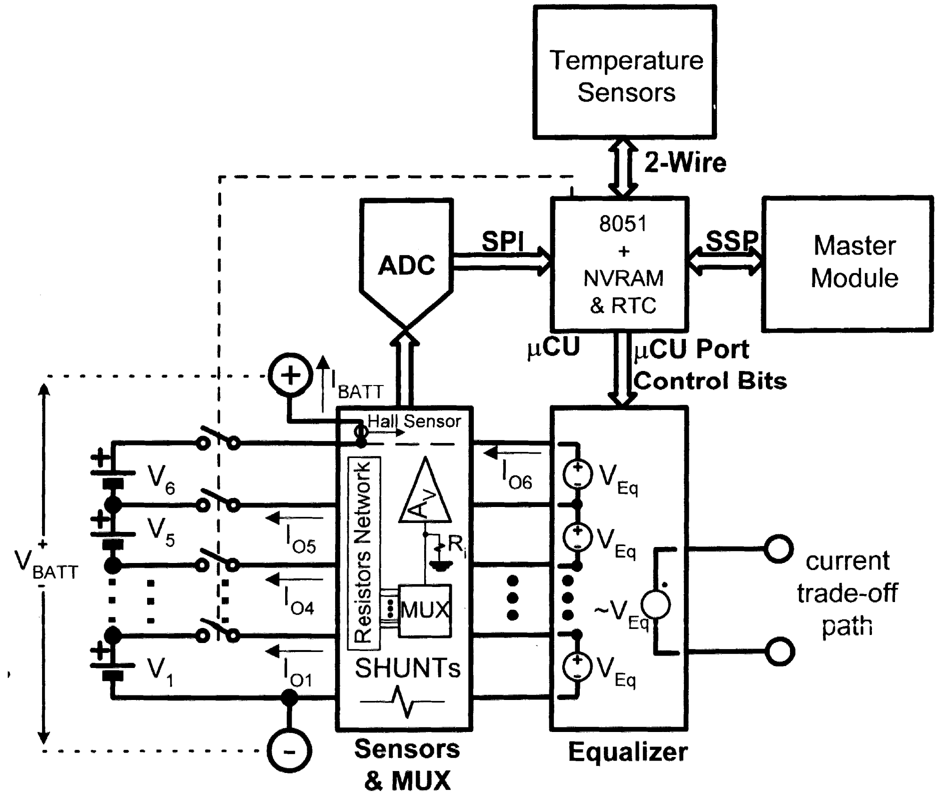

Fig. 3. Block diagram of the proposed SBM.

The SBM can have two types of sensors, one with analog output multiplexed in order to drive an A/D converter and another with digital output capable of communicating with the microcontroller through one of the commonly used interfaces (one-wire, two-wire, SPI, I^2C). The analog output sensors are current sensors and the digital interface sensors are mainly temperature sensors. The use of a limited wire interface gives the flexibility to adapt the system in every specific need by adding and removing sensors and minimizes the need to change other SBM hardware.

Each SBM should be able to measure the battery current. This enables the system to determine if any current leakage occurs somewhere in the battery string and also to estimate the battery state. Since, in practice, a compromise is made between sensor accuracy and sensor power dissipation, only one accurate sensor should be used in the master module, which supplies reference measurements to the other modules. Each module processor can give accurate current measurements from data collected even in the case of efficient but inaccurate Hall-effect current sensors by executing a sensor-conditioning algorithm.

The cell voltages and the current sensors outputs drive a resistors network, which weights appropriately their values. A multiplexer (MUX) selects sequentially each signal and drives an instrumentation amplifier feeding the A/D converter input. The microcontroller (μCU) controls the equalizer and scans all sensors sequentially. The μCU communicates by means of a standard serial port (SSP) with the master module.

Since only simple access to the battery cell interconnections is allowed, each cell current must be measured indirectly. Such a current measurement gives no additional losses before the start of equalization. Shunt sensors may be used in each cell equalization converter path [see Fig. 4(b)], but not in the equalization converter outputs [see Fig. 4(a)], where there is a common connection of two cell equalization converters and a two-cell interconnection. The separate cell equalization current measurements result in lower computation load and measurement errors, which are equal and minimal. The only disadvantage of this scheme is the slightly higher output resistance and losses of the equalizer, because each shunt is connected in series with the respective equalization converter [see Fig. 4(b)] and the total load current flows through this path, when the battery is fully disconnected from the module. However, this is not a major problem because usually the shunt's resistance is low compared to each equalization converter internal resistance.

Fig. 4(a) shows a scheme with shunt-current sensors connected at the equalizer outputs. The currents are assumed positive in the direction indicated by the arrows. Only $I_{\rm BATT}$ and $I_{O(n)}$ are measured directly. Regarding Fig. 4(a) the cell currents are given by

$$I_{\rm C6} = I_{\rm BATT} - I_{\rm O6} \tag{1}$$

$$I_{\rm C5} = I_{\rm C6} - I_{\rm O5} = I_{\rm BATT} - I_{\rm O6} - I_{\rm O5} \tag{2}$$

$$I_{\rm C4} = I_{\rm C5} - I_{\rm O4} = I_{\rm BATT} - I_{\rm O6} - I_{\rm O5} - I_{\rm O4} \tag{3}$$

or, in general,

$$I_{Cn} = I_{\rm BATT} - \sum_{n_{\max}}^{n} I_{On}. \tag{4}$$

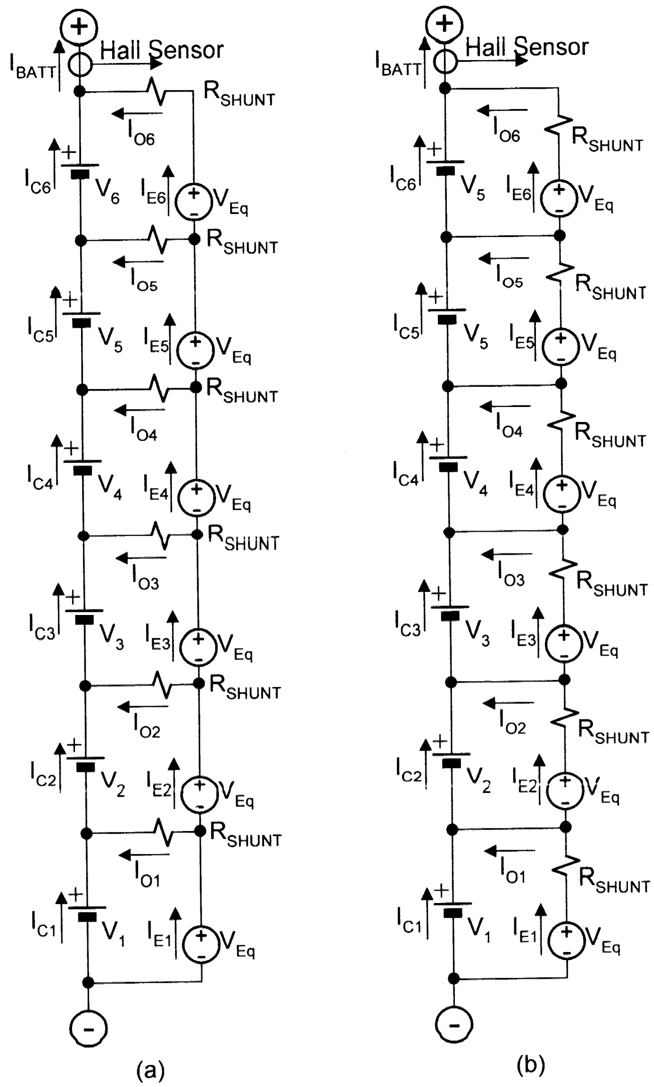

Fig. 4. Examination of current-sensing error. (a) Shunt-current sensors at the equalizer outputs. (b) Shunt-current sensors at the cell equalization converter path.

With the above approach, two problems are observed. First, the current of each cell cannot be calculated independently of the other cell currents and second, the total calculation error can be high, because it depends on the number of measurements taking place in each calculation. Thus, the above method gives errors, which depend on the cell position in the battery and which are always greater than the current error in the upper cell. The upper cell current error is equal to the sum of Hall-current-sensor and shunt-current-sensor errors. Since accuracy and power dissipation are competitive in high current sensors, this becomes a major problem and renders the method improper for use in an efficient SBM design.

Fig. 4(b) shows the scheme with the shunt-current sensor in the cell equalization converter path for direct measurement of the cell equalization current. In this scheme, the circuit analysis gives

$$I_{Cn} = I_{\mathrm{BATT}} - I_{En}. \tag{5}$$

It is apparent that this scheme has an acceptable calculation error, which is equal for each battery cell measurement, while the current calculation is easy for any cell inside the battery.

However, battery current measurements have another major problem, if the load is not known. The sensor is designed for a maximum current rating, but it may be operating for long periods of time with much lower current, for which the sensor error is much higher. If an A/D converter with a resolution higher than 8 bits is used, then the total measurement error can be kept within acceptable limits.

The microcontroller of the SBM can be chosen from the 8051 family. The final selection will depend on the exact algorithm used and on the number of cells that the SBM will manage. Since the measurements require more than 2-B numbers, the arithmetic operations must be done with a resolution of 32 bits or on floating point. This does not have to be implemented in hardware because the processing speed is limited mainly by the communication speed between the sensors and the microcontroller. A real time clock makes the system more advantageous and the coulomb-metric estimation more accurate. The clock may be placed in a microcontroller module or in a separate IC and may communicate with the microcontroller through a limited-wire interface.

The serial communications should be opto-isolated for better results. Thus, the loops formed by the serial communication wiring are decoupled and the low power system is protected against any malfunction due to noise interference. The master module that can communicate with each module using a module number and a global ID number can control all communications.

A. Proposed Algorithm

The microcontroller program must be able to recover under any error condition. There are many reasons that may cause errors, in case of system malfunction. High-voltage/current spikes, high electromagnetic fields, short-time supply-voltage drops, or even electrostatic discharges caused by humans touching conducting parts of the BMS may be produced and cause the microcontroller to go out of its program, or receive corrupted data. A microcontroller with a watchdog timer is suggested for this application along with software routines for error detection and correction. A nonvolatile memory helps the microcontroller operate without losing data after a power failure.

The serial port should operate by an interrupt signal, which uses a small serial buffer thus making module communications very fast. The communication routine checks the serial buffer and, if the first byte is the module ID or the global ID number, then the command issued by the master module is processed. Otherwise, the command is discarded and the program execution continues normally.

The proposed algorithm flowchart is shown in Fig. 6. Each task of the proposed algorithm is a complicated procedure and the simplified diagram of the flowchart shows the steps of the program to continuously perform measurement readings.

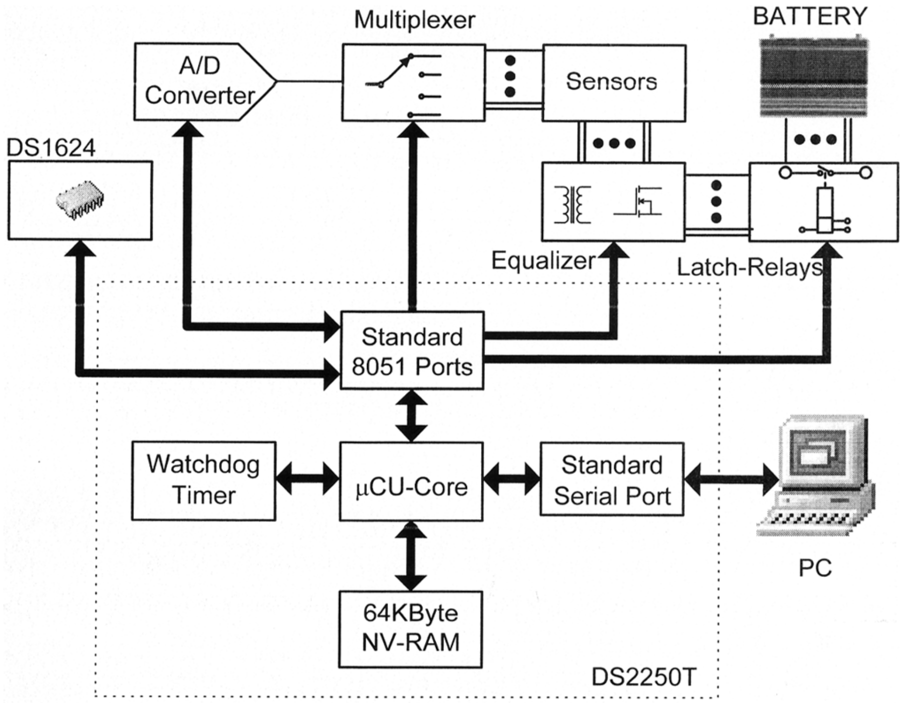

Fig. 5. Functional block diagram of the experimental SBM.

IV. SBM Experimental Results

In order to verify the theoretical design and identify the problems that show up in a real system, an experimental SBM prototype was constructed and tested in the laboratory. The system was based on a Dallas DS2250T microcontroller module. This consists of a DS5000FP microcontroller, 64-kB NV-RAM, a lithium battery cell, and a real-time clock. The DS5000FP chip has a watchdog timer and can handle its RAM without sacrificing any of the standard 8051 I/O ports. A 10-bit A/D converter was used and the input signal was fed through a level-conditioning amplifier and an analog multiplexer. The integrated circuit DS1624 chip was used as a temperature sensor. This chip uses a two-wire interface that can hold up to eight sensors thus making the design flexible and easy. The equalization converter was implemented using the MOSFETs type IRF44N and a multiwinding HF transformer wound on a type E65/32/27 ferrite core. The operating frequency of the equalization converter was kept at 16 kHz (relatively low, but within the working frequency range of the HF transformer core material) in order to avoid phase shifts in the current tradeoff path, even in very long strings. If appreciable cable lengths are required for string coupling, or operation at higher converter frequency is desirable, then a bidirectional switched-mode rectifier connected between the equalizer and the current tradeoff path, converts the coupling between the SBMs to dc form, eliminating the coupling problems.

The total error in cell voltage measurement was less than 50 mV. This error is acceptable for error detection purposes, but is rather high if the cell state-of-charge (SOC) is to be computed (corresponds to about 25% change to the SOC) and marginally acceptable for the control of the battery charging voltage in order not to seriously affect the battery lifetime. The error is due to the use of an experimental measurement circuitry in the prototype. The use of special devices would keep the error to substantially lower levels. The current measurements were less accurate because a Hall sensor was used (about 0.7 A in the range of 15 A), but this can be minimized in the BMS with sensor conditioning measurements performed by means of a high precision shunt in the master module.

As illustrated in Fig. 5, the microcontroller DS2250T controls the latch relays, the equalizer, and the multiplexer. Also, it communicates with the A/D converter and the temperature sensors. The μCU standard serial port is used to connect the system to a PC for both, control of the SBM and data acquisition from the SBM.

The program for the DS2250 was developed in a BASIC environment (BCI51). Pure assembly was used for the most routines and the high-level language was used mainly for the mathematical support, the interrupts, the watchdog timer, and the error handling. This software based on the algorithm described previously and designed in such a way, that the sensors were almost continuously scanned. This was done by examining the end-of-conversion bit of DS1624 before a temperature reading was taken and by serving only one request on the serial communication at each measurement loop. The A/D converter measurements were processed with 32-bit arithmetic routines and the most important software tasks of these that are shown in Fig. 6 were implemented. The experimental SBM performed more than six measurement loops per second.

In the place of the master module, a small circuitry able to provide the equalization timing signal and a serial port of a PC were placed. A DOS based program was developed, in order to be able to communicate with the SBM and obtain measurements

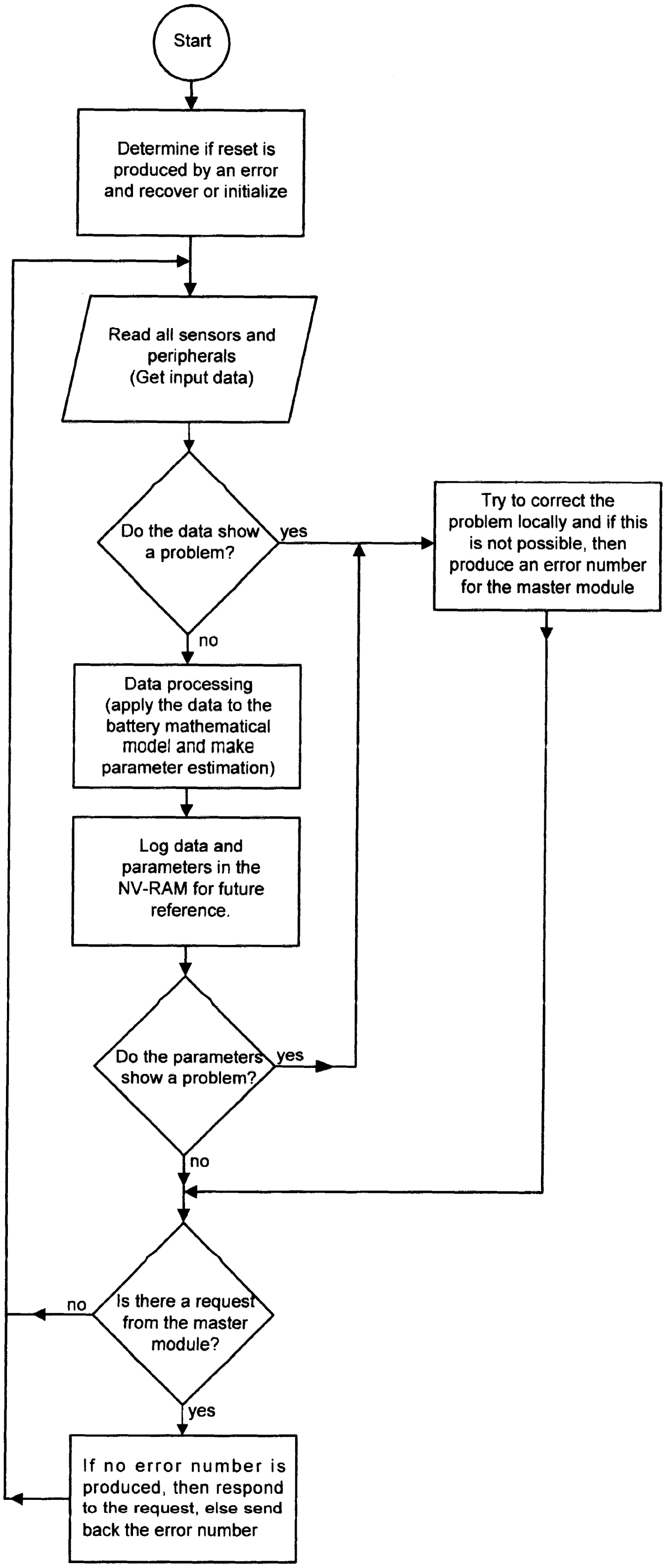

Fig. 6. Flowchart for the proposed SBM algorithm.

or give commands. If instead of measurement data, an error code came in, then a special routine was enabled specifically designed for error handling. The program had three parts: The first was able to show online the measurements obtained. This was very useful for the calibration of the sensors. The second part was able to request a full set of measurements, one every minute, and log it in a file, while the third was able to convert the log file in an MS-Excel-format file to enable the processing of the measurements under Windows.

The experimental SBM was connected to a 45-Ah lead-acid type battery and several try-outs were performed in order to optimize the algorithms and check for any problems during the operation. The test currents were kept under 10 A, because of a maximum current handling limitation of the latch relays. During the design process, care must be taken for the current limitation of the converter to be slightly above the maximum load current. Thus, the cell voltage is not reversed when the converter acts to replace a defective cell. The converter implemented for the experimental tests is designed to supply a maximum current of 10 A when its terminal voltage drops to 0 V. Fig. 7 shows the battery and the cell discharge behavior under an equalization scheme that starts the equalization at the moment that the cell voltage is reduced to 1.8 V.

This scheme of discharge equalization is effective and efficient because the equalization converter does not work continuously during discharge. The measurements were ended at the instant the processor supply voltage fell below 4.75 V. As it can be seen from Fig. 7 the battery current curve is not proportional to the battery voltage curve during the last few minutes of measurements. This happened because the Hall-current sensor had a minimum working voltage of 8 V and not because of the high-current-sensor errors discussed previously, but this is not a drawback because in normal operation the battery voltage should not drop under 10 V. For comparison purposes, measurements without he equalization were performed and are depicted in Fig. 8.

Comparing the experimental results with and without equalization, the effect of the equalization is visible and the total battery voltage curve is almost proportional to the single cell discharge curve.

Fig. 9 shows the battery discharge and the cell terminal voltages curves under equalization with one cell disconnected. It is apparent that some noise is superimposed over the measurement curves. This noise is introduced mainly at the terminals of the disconnected cell. The noise is negligible in a discharged connected cell, because of the high capacitance introduced by the cell. After many measurements were taken and after a few minutes of operation of the equalizer, it was observed that the terminal voltage of the disconnected cell was increased slightly. This is apparently caused by the temperature increase of the magnetic core of the equalization converter multi-winding transformer, because of its losses. The permeability of the core material increases with the temperature (for temperatures in the range of 0 °C–50 °C) and this improves the coupling between the transformer windings.

As it can be seen from the results of Fig. 9, the battery discharge curves are smooth and very similar to the single cell discharge curve, even under these circumstances. The disconnected cell terminal voltage remains positive until deep battery discharge. The voltage across the converter corresponding to the

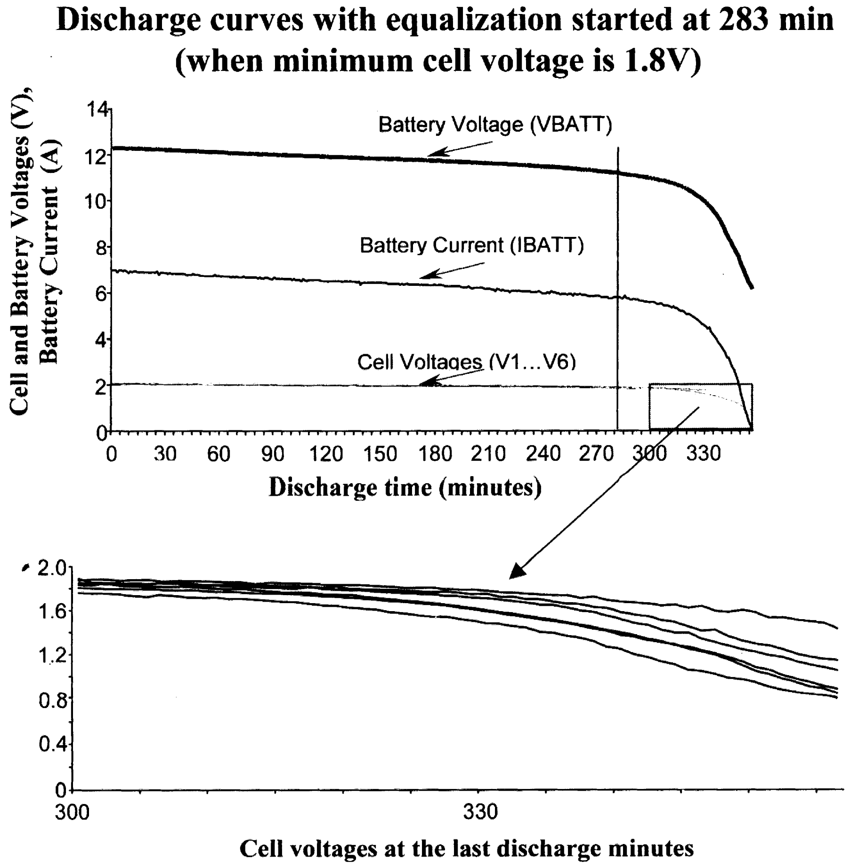

Fig. 7. Experimental discharge curves with equalization started when cell voltage is 1.8 V.

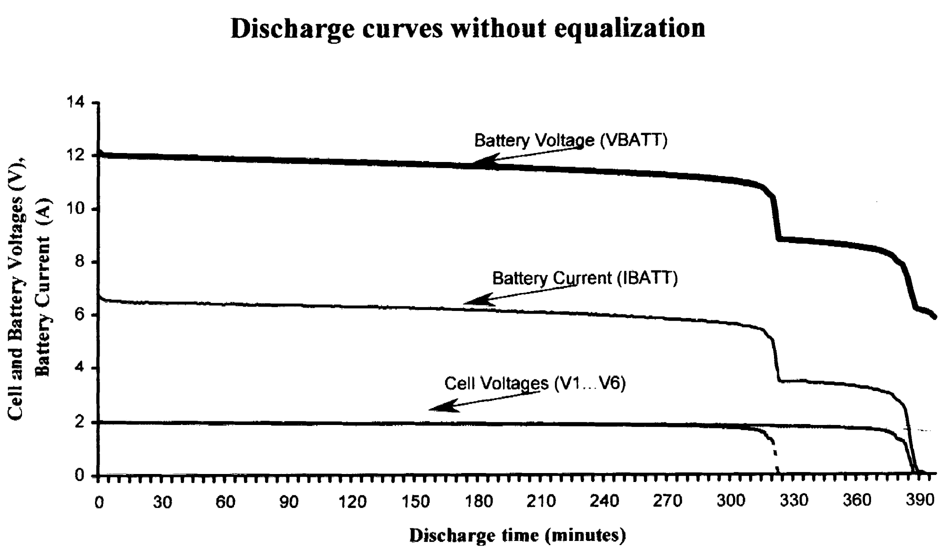

Fig. 8. Experimental discharge curves without equalization.

disconnected cell is lower than 2 V, because of the voltage drop on the converter internal resistance.

It must be noted that in a real system the battery operation must be terminated before such a deep discharge takes place and that the above measurements were taken only to show the effect and the operation of the equalization converter.

V. Conclusion

A design method for a novel generalized BMS has been presented and an experimental cell-based, modular, fault-tolerant system has been developed capable of providing charge and discharge equalization and battery protection. An SBM

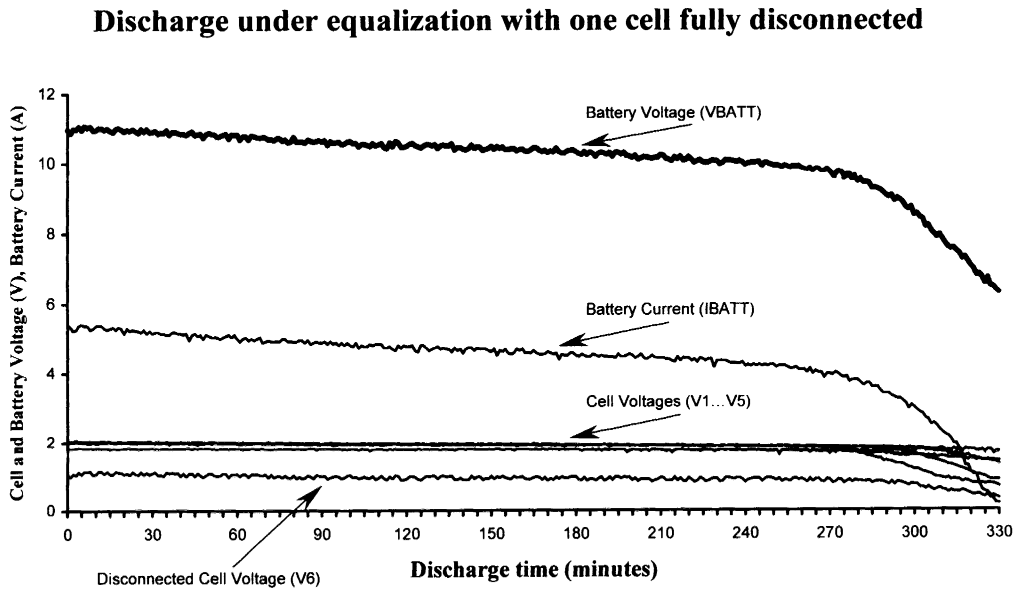

Fig. 9. Experimental discharge curves with one cell fully disconnected.

capable of communicating with a PC through a serial port and a specially written computer program was designed and tested in the laboratory. All problems encountered during the test and operation procedure were solved and the measurement errors were within acceptable bounds. The module was able to take more than six measurement sets per second and, consequently, it had a fast reaction to the battery problems. The battery discharge curves show the benefits of the discharge equalization schemes that were used.

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