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A Modular Battery Management System for HEVs

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ABSTRACT

Proper electric and thermal management of an HEV battery pack, consisting of many modules of cells, is imperative. During operation, voltage and temperature differences in the modules/cells can lead to electrical imbalances from module to module and decrease pack performance by as much as 25%. An active battery management system (BMS) is a must to monitor, control, and balance the pack. The University of Toledo, with funding from the U.S. Department of Energy and in collaboration with DaimlerChrysler and the National Renewable Energy Laboratory has developed a modular battery management system for HEVs. This modular unit is a 2nd generation system, as compared to a previous 1st generation centralized system.

This 2nd generation prototype can balance a battery pack based on cell-to-cell measurements and active equalization. The system was designed to work with several battery types, including lithium ion, NiMH, or lead acid. Surface mount technology is used throughout to reduce volume, mass, and cost. The weight and volume of the 2nd generation are estimated to be 70% and 87%, respectively, less than the 1st generation.

INTRODUCTION

Series connected battery packs in electric vehicles (EVs) and hybrid electric vehicles (HEVs) require monitoring equipment that is capable of measuring the voltages of individual segments (several modules/cells connected in series) in order to prevent damage and identify defective segments. As discussed in [1, 2], virtually all types of batteries can be damaged by excessively high or low voltages, and in some cases the results can be catastrophic. Lithium ion cells, for example, will ignite if they are overcharged, which equates to a high voltage. Therefore, once high or low voltage segments have been identified, some equalization process also must be used to re-balance the voltages. Imbalances are especially prevalent in EVs and HEVs since the batteries are frequently charged and discharged. Certain problems associated with these voltage measurement(s) themselves also were previously described in [3], along with possible solutions

In the following section, the approach and results of a study to investigate a modular battery management system for Evs and HEVs are provided.

APPROACH

To process the data at a central module (CM), such as that in Figure 1, these measurement circuits must transfer each segment voltage to a common reference level such as the system ground in the CM. This particular diagram shows a typical modularized battery management system that would use one of these transfer circuits in each of the local modules, LM#1–#4. In this system the 4 LMs are used to obtain data from 4 sections of the series battery pack, where each section contains 12 segments that require voltage measurements. This modularized approach drastically reduces the amount of wiring that otherwise would be required between the CM and the batteries. The transfer circuit in each LM is used to shift all 12 measurements to its local ground reference, i.e., G1-G4. These voltages are then multiplexed, fed to an A/D converter, processed by a local microcontroller, and galvanically transmitted to the CM via a serial data bus such as CAN 2.0B.

This transfer circuit approach provides several accuracy and cost advantages over previous methods, and it can be used for almost any number of battery segments. This is an important advantage since each LM can now measure a large number of segments to reduce the total number of LMs. For example, a 48-cell pack with 4 LMs each measuring 12 cells can be used in place of perhaps 12 LMs each measuring 4 cells. This represents a large cost savings since, as shown in Figure 1, each LM typically contains a multiplexer, A/D converter, microcontroller, and two galvanically isolated buffers for the serial data bus.

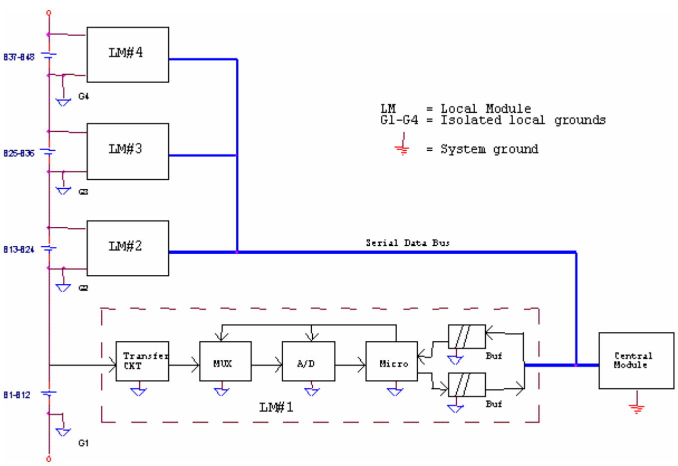

Figure 1. Modularized battery management system

To provide the greatest flexibility, this BMS was designed to have the necessary features required for Li-Ion, NiMH or lead acid batteries. Some of these include,

1. Modularization is used to avoid a large wiring harness, and each local module can service up to 12 cells. This provides a large reduction in the number of modules and the cost.
2. New types of voltage and current measurement circuits are used to provide higher accuracy. This includes an automated calibration procedure that stores correction factors in flash memory.
3. Battery data can be stored in flash memory in the CM and on disk in a PC.
4. All modules use CAN 2.0B serial communication for convenience and higher reliability.
5. When the battery is not in use, the BMS enters a low power sleep mode and measures the elapsed time in this mode. It also awakes periodically to perform various functions and then goes back to sleep.
6. Battery equalization uses a boost process instead of dissipation to improve battery efficiency.

SYSTEM REQUIREMENTS

Several types of advanced batteries are under study for EVs and HEVs, two of the most promising candidates being Li-Ion and NiMH because of their high energy densities. Some Li-Ion products are rated up to 125 Wh/kg [4], while the energy density of a NiMH battery can reach 80~90 Wh/kg [4]. However, the characteristics of Li-Ion and NiMH are very different, and this means different management requirements.

A Li-Ion battery weighs less than a NiMH battery with the same capacity and is more compact [5], but it also has more stringent management requirements because the battery may ignite if overcharged. This problem is especially serious for the big packs in EVs and HEVs where it could cause a fatal accident. To ensure safety, the voltage of each Li-Ion cell must be measured very accurately since this is the best indicator of the SOC [6]. It also means a fairly large number of voltage measurements must be processed every measurement cycle, eg., 48 cells every 2 sec. Balancing the cell voltages (equalization) also is more difficult because the simple method of overcharge with a small current (trickle charge) cannot be used. Instead, the cells must be balanced individually using a circuit such as the boost equalizer in this present system. Abnormal conditions for the cell voltage, battery current and temperature must activate an alarm and be handled promptly. Since the safety of the battery pack is dependent on the management system, the reliability of the management system becomes very critical. Therefore, various hardware and software safety features are required to secure the battery pack in case of malfunction. It is also very important to control the cost when adding additional features and enhancing existing functions. In addition, the size and weight need to be minimized to allow the BMS to fit into compact battery packs.

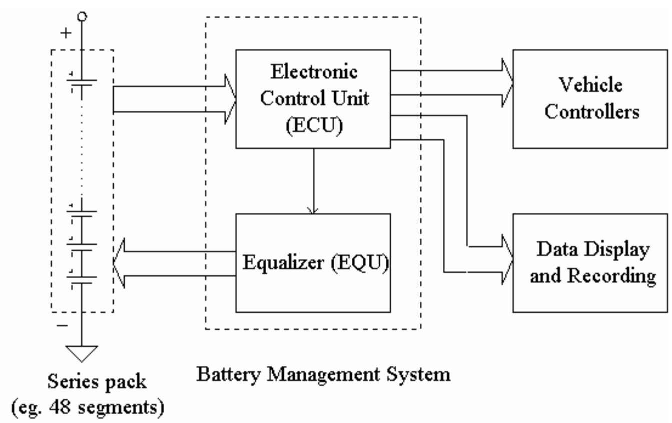

Figure 2. A conventional battery system

Since NiMH batteries are not as prone to the overcharge combustion problem as Li-Ion, their voltage measurement requirements are not as stringent. In addition, since voltage is not a useful indicator of the SOC of this battery [7], the voltage measurements do not require the same accuracy as Li-Ion, and individual cell voltage measurements are not necessary. Instead, the measurements can be reduced to a few segments of series connected cells, e.g., 6 segments of 8 cells each in a 48 cell pack. However, the leakage current is much higher than for Li-Ion, and the SOC can decrease considerable while the vehicle is parked for a few days. This high leakage along with the lack of correlation between voltage and SOC makes it much more difficult to determine the SOC. Because of this leakage, the parking time needs to be measured to predict the energy loss.

The block diagram of a typical battery system is shown in Figure 2. This particular version includes an electronic control unit (ECU) that monitors the real-time situation of the battery pack and an equalizer (EQU) that balances the charge levels of the battery segments.

The responsibility of the ECU consists of four functions: data collection, data processing, data transmission, and control. The ECU usually measures all segment voltages, a few selected temperatures, and battery current. It then analyzes the data and extracts information for battery protection and state of charge (SOC) determination. Some information is also transmitted to the vehicle data bus. The ECU also controls certain battery maintenance equipment, such as the battery cooler, heater, equalizer and autodisconnect switch (circuit breaker). A more sophisticated ECU will have the capability to control an on-board battery charger.

The purpose of the EQU is to minimize the SOC differences among the battery segments since such imbalances will reduce the usable capacity of the battery pack. However, the batteries in EVs and HEVs are frequently charged and discharged and are thus prone to imbalance. An EQU keeps the battery pack in balance by either charging the weak cells or discharging the strong cells. In some batteries, such as Li-Ion and lead acid, SOC differences are directly proportional to voltage differences. For those batteries the equalizer strategy could depend on voltage [8]. For NiMH, cell voltage is not related to SOC [7], and a more complicated strategy is required [9] [10].

A battery string with a fairly high voltage of 100-400VDC is commonly used in EVs and HEVs to supply high power without an overly high current. The string is usually divided into several segments to be managed. Older BMS designs typically take the whole battery pack as one segment. This kind of BMS is cost efficient since it requires significantly fewer components and is less complex in terms of data processing and communication. However, it does not offer the ability to measure and balance individual cells or segments in the pack. For the more volatile Li-Ion battery, each individual cell must be measured and balanced.

PRESENT SYSTEMS

Battery management technology is quite mature in portable equipment applications such as laptop computers and cellular phones. Companies like Texas Instruments [11], Power Smart [12] and Philips [13] have all developed battery management IC products, and there are systems for portable equipment based on these ICs [14]. However, the application environment for EVs and HEVs is very different from that in portable equipment in regard to items such as battery pack size, charge/discharge current amplitude and frequency spectrum, temperature range and EMI. These differences make the BMS for EVs and HEVs a much more complicated system, and it needs a very different design.

A few modular BMS systems for large battery packs are now commercially available [15-17], and some battery manufacturers have designed systems specifically for their own battery packs. A review of these designs indicates that while undoubtedly functional, they do not have certain features demanded by advanced EV/HEV batteries. Some of these features are very critical and require new technologies.

Some of these BMSs do not have SOC determination capability, so it will not be possible to hold the SOC in the desired range, and the user will not know the remaining energy in the battery. To determine the SOC, the BMS will require an accurate charge measurement circuit and a sophisticated algorithm that is designed using knowledge of the battery characteristics.

Voltage measurement is another problem for many of these earlier systems. First, the accuracy is not sufficient for a Li-Ion battery, and this might impair safety or reduce the usable capacity of the battery. Furthermore, the time period between each cell voltage sample is so long that the battery current could change significantly during this time period. Since battery voltage changes with the current, this will skew the voltage measurement data.

The communication schemes in some of these systems are also questionable. Many systems use an RS232 bus for data communication, which is not designed with strong error management capability and EMI immunity. Possible communication errors or failure may cause serious safety problems, especially with a Li-Ion battery.

Dissipative equalizers used in most of the present BMSs [15, 16] dissipate the energy in all the cells until they reach the same the level of the weakest cell in the battery pack. Although the idea is quite simple and the cost is low, it obviously has low energy efficiency.

The BMSs in [15-17] have a distributed structure, where local units serve one battery segment and send data to a central unit. Compared to a centralized structure, the distributed structure is more flexible for different types of batteries and numbers of segments. It also dramatically reduces the size and weight of the wiring harness as well as the wiring labor. However, since each of the local units in these systems only measures one battery segment and there is a microcontroller in each local module, the cost of the whole system is quite high.

PROPOSED SYSTEM

The intent of this research is to develop new technologies that will lower the cost and improve the safety and performance of battery systems in order to make them practical for EVs and HEVs. An engineering prototype using these new technologies was designed, built and tested. This prototype also has certain features that enable it to be used with several types of batteries such as Li-Ion, NiMH and lead acid. Compared to previous systems, the new system provides large reductions in cost, size and weight, all of which are of critical importance in EVs and HEVs.

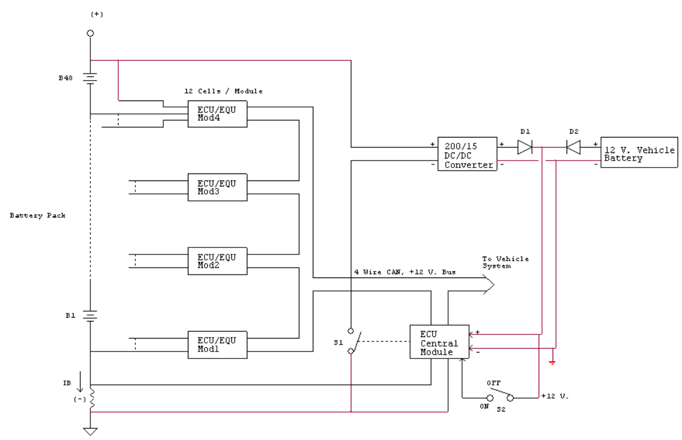

Figure 3. New modular ECU/EQU system

Figure 3 shows the block diagram of a new modular system designed for a Li-Ion pack. This particular system has four local ECU/EQU modules, one central ECU module and a DC/DC converter module. Each local module serves 12 battery segments because the Li-Ion pack has 12 segments (2VDC~4.2VDC per segment) in each battery module. By changing certain components, it can be redesigned to serve even more segments, e.g., 16 or 24. Compared to earlier centralized systems, this modularized structure reduces component costs greatly. It also simplifies installation and wiring work. Each local module is a combination of a local ECU unit and a local EQU unit, where the ECU controls the EQU. All the local ECU units and the central ECU unit communicate directly via the CAN 2.0B vehicle data bus. Using CAN for both internal and external communication simplifies the system since it offers speed and reliability advantages. When the system is turned off by S2, the Central enters a low current "sleep" mode so it can retain data in its SRAM and measure the off-time.

The system can be powered either by the 12V vehicle battery or by the 48 cell battery pack via the DC/DC converter in Figure 3. The controlled switch S1, is closed whenever the Central ECU routes power to the Locals, and the system will be powered by the DC/DC converter as long as the 12V (actually 9VDC~16VDC) battery remains below 15VDC. This arrangement is used so equalization can be done during park without draining the 12V battery. When the system is in sleep mode during park, S1 is open; the DC/DC converter is off; the Central is powered by the 12V battery; and the power to the Locals is turned off by the Central. During sleep mode, the Central only draws about 0.8mA., which is an acceptable drain on the 12V battery. The DC/DC converter is turned off during sleep because even at small loads such as 0.8 mA., its input current is actually several mA. This drain would be excessive for the 48 cell battery pack during a long parking period. All of the microcontroller requirements can be met with the Infineon SAF505CA, which has a CAN 2.0B controller and a 10 bit A/D.

The responsibility of local ECU unit includes:

- Voltage measurement
- Temperature measurement
- Communication
- EQU control

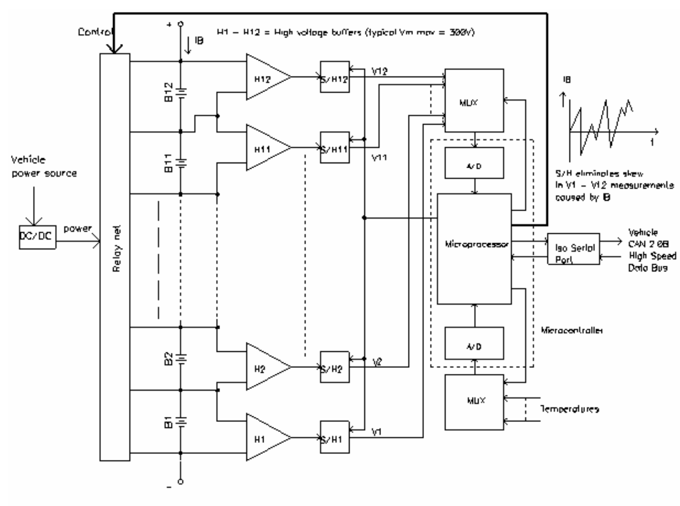

Figure 4. New local ECU/EQU module for 12 cells

The responsibility of central ECU unit includes:

- Local module on/off control
- Voltage measurement synchronization among local modules
- Data collection, data processing and communication
- Battery charge and current measurement
- Battery State of Charge (SOC) determination
- Safety features
- System monitoring during sleep mode
- Battery maintenance equipment control

This version uses a selective EQU in each local module, which charges the weakest segment of the local pack with a constant current. Its intelligence is provided by the local ECU, which also controls various safety features.

Since this EQU functions by charging a selected cell, it is important to supply the operating power from the Central ECU instead of from the local cells, i.e., a 4 wire bus should be used instead of a 2 wire bus. The reason for this is that if the Local ECU fails, it might not be able to turn off its EQU. This could result in overcharging for a Li-Ion cell and cause an explosion. With a 4 wire bus, the Central ECU can remove all power to the Locals in the event of a Local ECU failure.

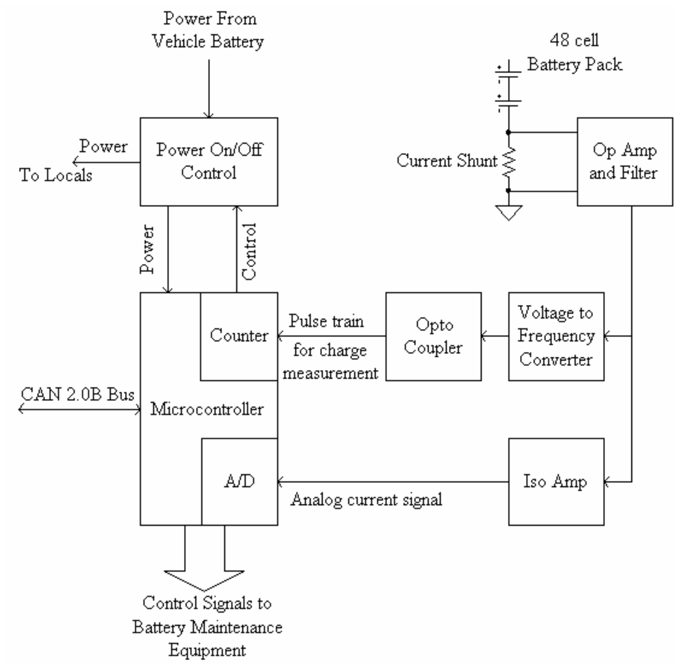

Figure 5. New Central ECU module

Local Module - Figure 4 is a block diagram of one of the local modules. The ECU components are to the right of the pack and the EQUs are to the left. H1-H12 is a voltage transfer circuit that shifts the 12 cell voltages to a common reference level. By using an operational amplifier based transconductance amplifier, the transfer circuit design is simple and cost effective. It also has a very stable gain over a wide temperature range, e.g., from –30oC to 60oC. This feature is critical for achieving the high accuracy measurements demanded by Li-Ion. An automated calibration technique has been developed to reduce initial tolerance errors. This is done using a calibration program stored in the microcontroller, where the program stores correction factors in flash memory. Sample and hold circuits S/H1 – S/H12 are used to eliminate the measurement skew problem so that all voltage samples are performed within a few microseconds.

The EQU in Figure 4 is a selective boost type that uses a DC/DC converter with a constant current output and a series of small telecommunication relays. The relays are controlled by the local ECU to direct the current into the lowest voltage segment in the battery module. This results in much lower losses than dissipative EQUs, which reduce all segment voltages to the lowest voltage in the battery pack. This type of EQU also will equalize an unbalanced pack much faster, since lower losses allow higher EQU power levels. It avoids the electro-magnetic interference (EMI) problems associated with the ramp equalizer [8], and it also eliminates the expensive transformer which is used in the ramp. Another advantage over the ramp is that a selective EQU can be used to equalize NiMH batteries whose SOC does not vary directly with voltage.

Central Unit - Figure 5 is a block diagram of the new central ECU module. At the beginning of each operation cycle, this central unit broadcasts a CAN message to start the voltage and temperature measurements in all the local modules. It checks to make sure that the local units work properly and transmit the required message within a specified time period. Battery current is measured using an A/D converter to provide over-current protection.

A charge measurement circuit with continuous analog integration and a digital output greatly improves the accuracy of the SOC calculation. It uses a voltage to frequency (V/F) converter and a pulse counter to integrate the charge and discharge current over the entire range of ±300A. These measurements are accumulated continuously over each 2 sec. interval and used to update the SOC during operation. Dividing each charge increment by the 2 sec. interval provides another way to measure the average current value, but it has a slower response than the method using an A/D. However, it has been found to provide slightly better accuracy.

When the battery pack is not in use, the system will switch from active mode to power-down mode (sleep). In power-down mode, it turns off the power to the local modules and the support power in the central module. Only the power to the microcontroller, external timer and a few logic circuits remains, so that the drain from the 12V vehicle battery is only about 0.8mA. The external timer wakes up the microcontroller every 4 sec. to record the off-time. The off-time measurement can then be used to estimate the self discharge, which is required for NiMH batteries. This timer also provides the ability to let the system check the status of the battery pack periodically, e.g., every one hour, during park.

At each 2 sec. measurement interval, the voltages, temperatures and current data are processed and sent to both a CAN 2.0B and an RS232 serial data bus. If one or more of the battery parameters exceed certain limits, the Central ECU sends out an alarm and a diagnostic code. In some cases additional action is taken, such as turning on a fan or heater for the battery pack. Other actions at the vehicle controller level might include limiting charge/discharge current or opening the battery pack circuit breaker.

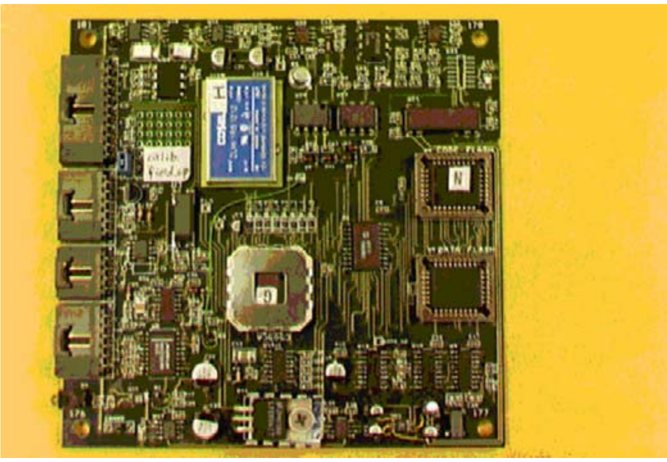

Figure 6. Central ECU circuit board

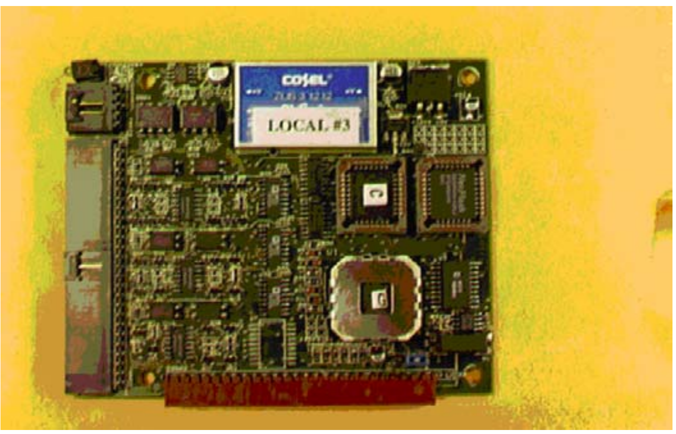

Figure 7. Local ECU circuit board

A prototype BMS based on the description of the previous sections was developed. Photographs of the Central ECU and the 12-cell Local ECU are shown in Figures 6 and 7, respectively. These boards have the following dimensions:

Central ECU: $12.7 \times 12.7 \times 1.5\ (cm)^3$

Local ECU: $10.2 \times 11.5 \times 1.5\ (cm)^3$

EXPERIMENTAL RESULTS

Voltage measurements – As described in [18], each Local ECU uses voltage measurement circuits that employ the following techniques:

1. Calibration factors stored in flash memory to reduce errors due to initial tolerances.
2. Operational amplifiers to reduce errors due to temperature variations.
3. Sample/hold circuits to reduce the voltage skew problem.

The prototype modular BMS was tested with a 48 cell Li-Ion battery pack (187V., 3Ahr)to verify its functionality and performance.

A series of tests between –20ºC and +50ºC were conducted with one of these modules connected to a 12 cell Li-Ion pack. The results indicate a maximum error of -9mV for cells which had an average voltage of about 3.5V. This corresponds to an error of –0.26%, which is about half the magnitude of the maximum predicted error of ±0.51%.

Current (I) and Charge (Q) Measurements – Although they share some of the same of measurement circuitry, the required accuracies for I and Q measurements are quite different. I is used primarily for protection purposes and usually does not require a high degree of accuracy, i.e., ±5% may be adequate. Q however is obtained by integrating the I measurements over long periods of time, and the error is cumulative. This means that if the measurement period is long enough, the error will eventually become unacceptable, no matter what the accuracy is. This means the SOC must be reset periodically to some accurately known value. Lead acid and Li-Ion batteries can use the stabilized open circuit voltage to determine the SOC while the battery is at rest. However, NiMH batteries cannot use this technique because their voltage is almost constant over a wide SOC range. In this case it will usually be necessary to program the on-board charging system to periodically charge the battery to SOC = 100% in order to reset.

In spite of the eventual need for reset, it is still important to strive for Q measurements that are as accurate as possible. It is obvious that the higher the accuracy of the accumulated Q, the longer the period before reset is necessary.

The central ECU measures the accumulated Q in the following manner. A resistive shunt is used to measure the current, and the shunt voltage is applied to a voltage-to-frequency (V/F) converter. A counter then counts the number of pulses at the V/F output over a fixed time interval. Q is thus obtained from a very accurate integration of the measured current, and the circuit avoids many of the offset and drift errors of analog integrators. As with the voltage measurements at the Local ECUs, the current measurement circuit is also pre-calibrated, and initial tolerance correction factors are stored for various points over the entire measurement range.

To evaluate the ΔQ error over an extended period of time, the shunt voltage, Vs, was varied over a period of 36 minutes. The SOC reset feature was de-activated during these tests to insure that coulomb counting would continue uninterrupted over the entire 36 minutes test period. As indicated in the figure, the BMS measured ΔQ was 222A.sec. at the end of the test whereas the manual current x time measurement was 223.2 A.sec. This corresponds to an error of 0.54%, which is actually better than expected. Naturally, the error can be expected to increase if the temperature also varied.

Equalization Test – At each 2 second measurement interval, if the EQU is not charging a cell, the Local ECU compares the lowest of the 12 cell voltages, Vmin, with the highest voltage in the 48 cell Li-Ion pack, Vmax. If Vmax – Vmin > 40mV, the ECU commands the EQU to start providing an additional 120mAdc boost to the low cell. Once connected, the boost continues until Vmin ≥ Vmax. The EQU is then disconnected, and the cell is locked out for the next 2 minutes. This is done to prevent a high resistance cell from cycling the EQU on and off every 2 seconds. This also allows other cells to be equalized and prevents unnecessary operation of the relays that route the current to the low cell.

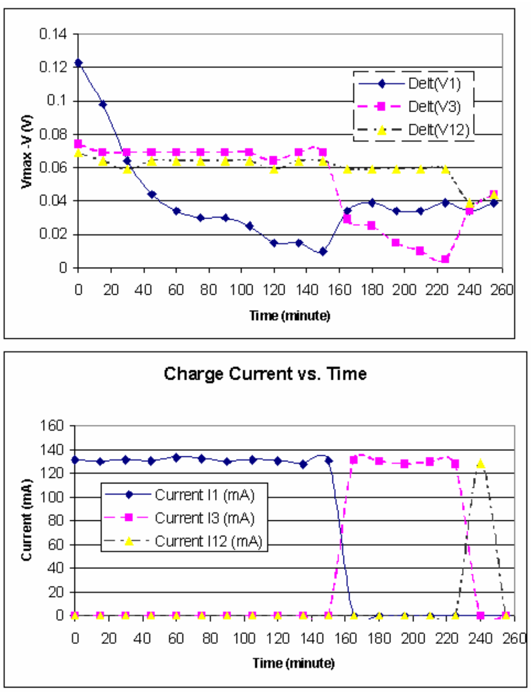

Figure 8. Equalization test results

Although the EQUs will re-balance an unbalanced pack, their main purpose is to prevent an unbalance from occurring in the first place. Unbalance prevention can be achieved with a fairly low current such as the 120mAdc used here, and this choice significantly reduces the size and cost of the EQU. However, a low current obviously takes longer to re-balance a badly unbalanced pack.

The following procedure was used to measure the time required for the EQUs to re-balance an unbalanced pack.

1. All 48 cells in the pack were initially balanced.
2. Three cells in each module (12 cells each) were discharged to SOC levels that range from 13% to 27% below the SOC of the maximum voltage cell in the pack. Exact ΔSOC values from each of these cells are ΔSOC1 = -26.7%, ΔSOC2 = -16.1%, and ΔSOC3 = -15.1%. Although imbalances of this magnitude are commonly used for testing equalizers, ΔSOC's of this size would be unusual in actual practice.
3. The system was turned on, and ΔV = Vmax – Vn vs. time (n = cell no.) was measured for each of the 3 cells. Cell currents were also measured.

The EQU test results are shown in Figure 8. Cell #1 which had the largest ΔV was re-balanced to less than 40mV within 50 min. This cell continued to equalize until 150 min. elapsed since its voltage must be increased until V1 ≥ Vmax. Cell #3 was then equalized for about 75 min., and finally Cell #2 was equalized for about 30 min. to complete the process. All 3 cells were equalized within 255 min. It should be noted that since the currents were only measured every 15 min., the on-off transition times in Figure 8 are not precise. The rise and fall times of the currents actually occur in less than 1ms instead of the 15 min. interval on the graph.

The first point at t = 0 sec. in Figure 8 is the initial ΔV based on the open circuit voltages. ΔV drops abruptly when the EQU turns on because the equalizer current will cause Vmin to rise due to the effective cell resistance. Calculations based on the results of these tests indicate the capacity of these cells is about 2A.hr. This calculation uses the incremental amount of charge along with SOC vs. open circuit voltage curve provided by the manufacturer. The open circuit voltage for a cell at the end of the test is the voltage after it is disconnected from the EQU, which is about 40mV lower than with the EQU.

PHYSICAL SIZE AND WEIGHT

One of the primary goals of this new modular BMS (Generation 2) was to drastically reduce the size and weight of a previous centralized BMS (Generation 1) that was used on two experimental HEVs. This earlier system also was designed for 48 cell LiIon battery packs. As compared to Generation 1, the volume of Generation 2 was reduced by 87%, while its weight was reduced by 70%.

These size and weight are based only on the modules and do not include the differences in the wiring harness. However, the reduction in the harness size for the modular BMS undoubtedly will be even greater than for the modules themselves. The old harness between the ECU, EQU and battery used over 130 wires. Part of this large number was due to the fact that the ECU and EQU could not use the same voltage sensing wires to the cells. This was because the EQU currents caused slight voltage drops that affected the accuracy of the ECU cell voltage measurements. In the new modular system, the Local ECU/EQU modules are mounted on the battery modules so the sensing wires are very short and can be shared. Their weight is insignificant because of their very short length. The cable between the Local ECU/EQUs and the Central ECU contains only 4 #22 AWG wires.

Figure 9. Size comparisons for Generations 1 and 2

Figure 9 illustrates the size reduction that was achieved by the Generation 2 system. It also allows for easier packaging of the components and is less expensive. This improved system was intended to help auto manufacturers, battery manufacturers, and battery pack integrators improve performance while achieving higher energy efficiency and lower emissions.

CONCLUSION

A modular battery management system was developed and tested. This BMS provides important advantages in these basic areas: voltage measurement, accumulated charge measurement, and equalization. Voltage measurement is achieved with a very accurate circuit that also provides up to 12 measurements per module to reduce cost. The charge measurement circuit employs an accurate V/F converter in conjunction with a counter to integrate the current waveform. This extends the time before it is necessary to reset the measurement. Equalization is accomplished using a relatively simple current routing circuit that boosts the charge on low voltage segment instead of the more common method of discharging higher voltage segments. All features have been extensively tested and verified on a 48 cell Li-Ion battery pack. Surface mount technology is used throughout to reduce volume, mass, and cost. The weight and volume of the modular system are 70% and 87%, respectively, less than the central system.

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