

Design and development of a battery cell voltage monitoring system

by Nick Prinsloo and Dr. Ian D de Vries, Cape Peninsula University of Technology

The purpose of this project was to investigate various methods that would allow accurate measurement of individual cell voltages that are all connected in series to make up a battery pack. Methods such as isolation amplifiers, opto-isolators, DC-to-DC converters and a series of new chips designed specifically to do this task, were all evaluated in terms of complexity, performance, measurement range, accuracy, size and in particular cost.

A system was required to measure cell voltages and log the information to a PC. This would provide a detailed history of the cell voltages and how the battery stack performs over time. Having a system that measures cell voltages accurately gives the possibility of doing cell balancing which will improve cell lifetime and performance.

Batteries are used daily to provide power, mobility and backup to equipment. The ability of cells to correctly and reliably perform these tasks depends on their charged status. Cells are manufactured to produce a certain amount of ampere hours (Ah) at a rated voltage. The closer cells are to their peak charged levels the better they will perform the required work, and for increased periods.

Measurement of cells in a battery stack is important for the following reasons:

- The present state of the stack can be monitored.
- When charging the stack, the voltage has to be known so that overcharging does not occur and when discharging the stack so that over discharging does not occur.
- Accurate voltage measurements of individual cells will allow the use of equalisation techniques to balance cells.
- By measuring and logging data the overall health of the stack can be calculated and future calculations can be made by observing specific parameters.

Specifications

The following desired specifications are based on set parameters after careful considerations of what features are required from a battery management system (BMS) for a 24 cell battery stack.

According to Bergveld [1] a BMS needs to include all functions that are required to ensure proper battery operation and use.

Hence a BMS needs to control charging, discharging, measure individual cells, prevent over discharge, undercharge and

Parameter	Specified
Current consumption	$\leq 1 \text{ mA}$
Voltage measurement range	$0 - 5 \text{ V}$
Individual cell overvoltage range	7 V
Overall voltage measurement accuracy	$\leq 0,25\%$
Main isolation barrier, if isolated	$\geq 2 \text{ kV}$
Measurement time for all cells	$< 100 \text{ msec}$
Measurement accuracy per cell	$\leq 10 \text{ mV}$
Cells in stack	$\geq 24 \text{ cells}$

Table 1: Desired system specifications.

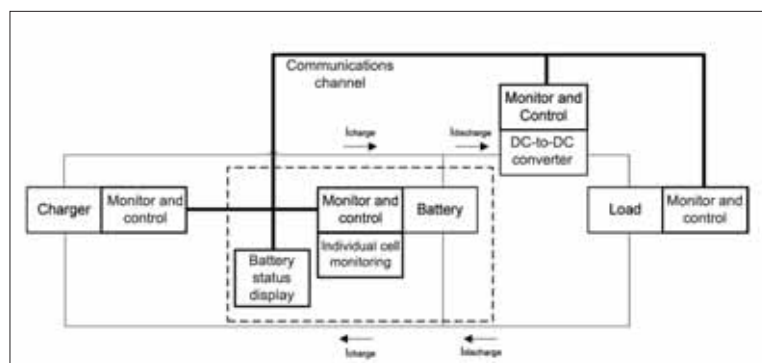


Fig. 1: Example of a complete BMS [1].

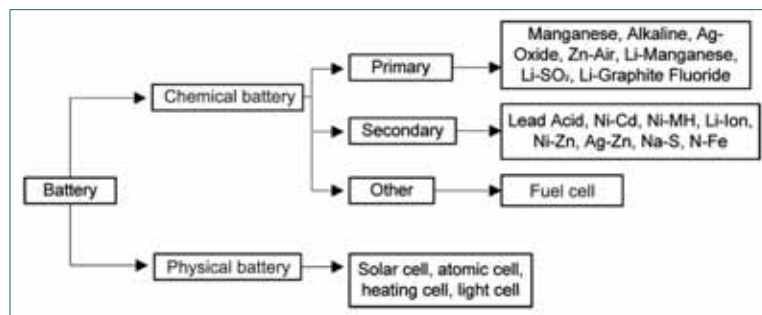


Fig. 2: Battery cell types and chemistries [2].

overcharge of individual cells. It should also measure and display the energy stored and capacity of the battery pack.

Commercial BMSs

Problems with commercial BMSs are the following:

- Price, even simple units are costly.
- Size and complexity do not allow them to be installed in a small space.

- Designed for specific cell stack size and cell chemistry.
- Most do not perform any cell balancing, some may perform passive balancing.
- The design covered in this paper attempts to address the shortcomings of current BMSs.

Batteries, comprised of series stacked cells, are divided into different categories as

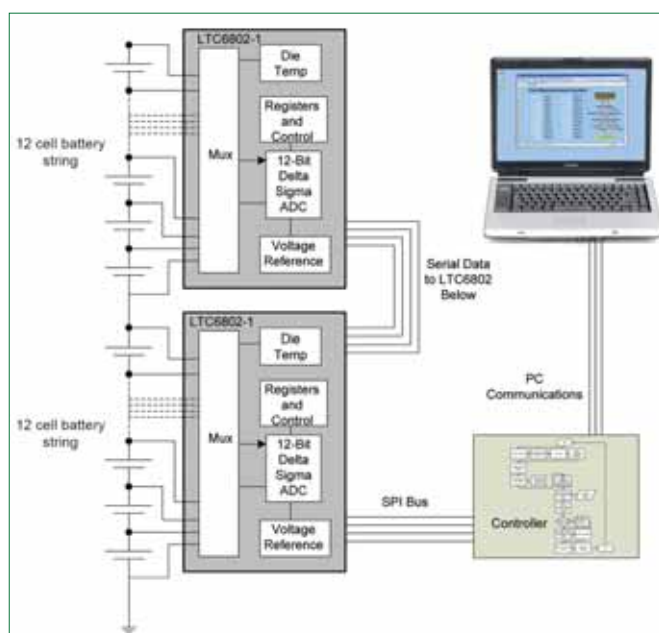


Fig. 3: Simplified system diagram of prototype setup.

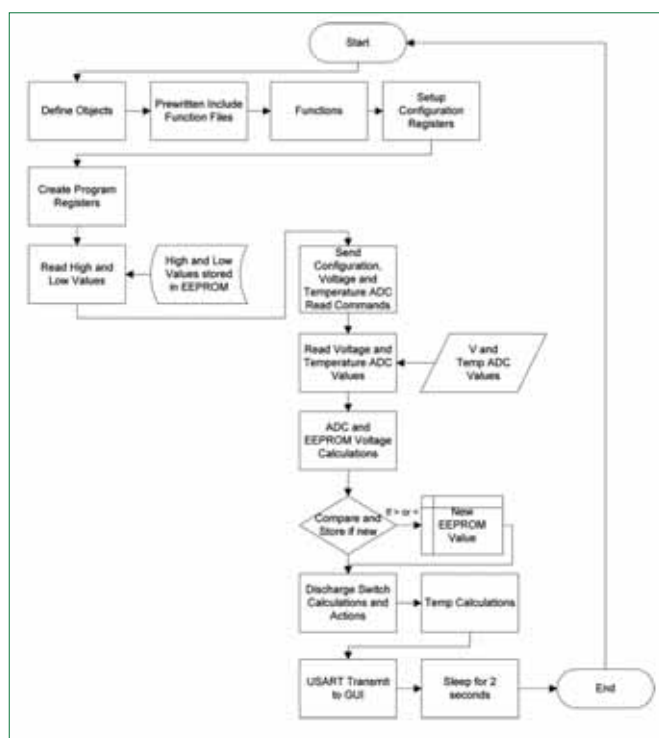


Fig. 4: Flowchart showing program structure.

stack a problem arises in that it is floating at a high common mode voltage which rises as the stacked cell count is increased as well as the position of the measured cell in the stack. This mandates the need then for either level shifting down to a common reference node for all cells without losing accuracy of that cell voltage. Level shifting can only be done practically for a few stacked cells, there after an isolated measurement should be done [7].

The following topologies were identified for investigation and were prototyped:

Isolation amplifiers

Isolation amplifiers contain an input that is separate from its output through galvanic isolation. The voltage information is transferred from the input to the output through three different methods: transformer, capacitive and optical coupling.

Isolation amplifiers are expensive and complex which make them unsuitable for this design. Although high accuracy and low current consumption makes isolation amplifiers desirable, high costs and difficulty in connecting them in a system that would allow twenty four individual cell voltages to be measured makes isolation amplifiers a non feasible option.

Optocouplers

Unlike isolation amplifiers, optocouplers do not convert the potential difference at the input to a determined switching waveform. The input potential difference generates a constant current through a light emitting diode (LED) which radiates light onto a receiving phototransistor. Ideally the input current should be linearly proportional to the output current when the current transfer ratio (CTR) is one, but having the CTR stay linear over the full operating and temperature range is unlikely. The following problems are faced when using optocouplers: Non-linear, measurements vary with temperature, measurement range limited at low voltages, require complex analogue multiplexers and accurate analog to digital conversions for complete system operation.

Simulation results showed promise, but measured results were different from simulation results. Because of the low accuracy this circuit cannot be used to accurately measure the voltage of a cell.

Isolation transformer

An alternative to isolation amplifiers that are produced by manufacturers is to build them. Using different techniques, the voltage information can be transferred over an isolation barrier, while still being accurately measured as was the case for the isolation amplifiers.

A circuit that uses a signal transformer and a current pulse generator to isolate

shown in Fig. 2. Of those only secondary cells will be focused on in this paper.

Three types of rechargeable cells are mainly used in contemporary systems. They are lead acid, nickel metal hydride (Ni-MH) and lithium ion (Li-Ion).

Different types of cells are made of different chemical compositions and because of this the different cells have different voltage levels and different types of charging routines are needed. The state of charge (SOC) is reflected in the voltage and allows the charged state of the cell to be calculated [3, 4, 5, 6].

Thus, if highly accurate voltage measurements can be taken, enough information can be obtained about the stack to make future calculations. However, measurement of a low value DC voltage is easily measured using specific integrated circuits (ICs). When an individual cell voltage in a high cell count battery stack needs to be measured it cannot be done with these ICs due to the high stacked common mode voltage with respect to the referenced ground of the system [3, 4]

The need for galvanic isolation

When measuring a cell in a high voltage

the input from the output was tested in a study by Linear Technology. The system design can be seen to be neither simple nor small [7].

The isolation transformer will, when the primary is pulsed with a short current pulse, produce a voltage related to the secondary voltage on the primary winding. The secondary voltage that appears on the primary winding is the cell voltage plus the forward diode drop of the transistor along with an added error from the transformer. The voltage on the primary winding is left to settle for a short period and then sampled where after gain correction can be done electronically or with a software algorithm.

Accurate results can be obtained using this topology. A small transformer size can be used as no power is transferred through the transformer. The topology suffers when multiple of these single sections are put together, as the system becomes complex, slow and less accurate with temperature change.

Extra circuitry is required to negate the effects of the transformers negative recovery excursion after being pulsed. This topology, like the isolation amplifier, would only work satisfactory when small cell stacks need to be measured.

The following problems are faced when using the isolation transformer: Measurements vary with temperature, requires complex analogue multiplexers and accurate analog to digital conversions for complete system operation.

DC-to-DC converter

A DC-to-DC converter can also be used to measure cell voltages while providing galvanic isolation. A prototype system for this topology was available. It was used to test if high currents could be transferred from one cell to another when a small potential difference between cells exists as part of active cell balancing tests [6]

The circuit consists of an H bridge with transformer isolation. The transformer was chosen to be a planar transformer to decrease overall footprint while providing low leakage inductance and a high efficiency. With a 1:1 transformer and 50% duty cycle for both sides of the PWM controllers the voltage on the secondary side was directly transferred to the primary side.

This topology delivered excellent results and could be used as an accurate cell measurement device with very little drift over a large temperature range. The prototype was great in size, but could be scaled down using low power components. If the previous multiplexer system example is followed the topology still suffers from being too complex to connect in a large system. The following problems are faced

Parameter	MAX11068	ATA6870	LTC6802-1
Best application	Any size pack, 8 to 1,4 kV	Medium pack, 10 to 355 V	Any size pack, 10 to 1 kV
Connection topology	Modular, 1 IC every 12 cells.	Modular, IC every 6 cells.	Modular, 1 IC every 12 cells.
Minimum voltage reading measurement	0 V	0 V	0 V
Maximum voltage reading measurement	5 V	5 V	5 V
Voltage measurement accuracy	0,25% over full range	-	0,25% over full range
Voltage measurement ADC	Successive approximation	Delta sigma	Delta sigma
Voltage measurement speed for 12 cells	8 ms	-	13 ms
Internal communication protocol	I2C	SPI	SPI
Standby current (μ A)	1	10	50
Operating current (mA)	2	15	1.5
Cost per 100 ICs (US\$)	-	7,00	11,59

Table 2: Table of comparison between MAX11068, ATA6870 and LTC6802-1 ICs.

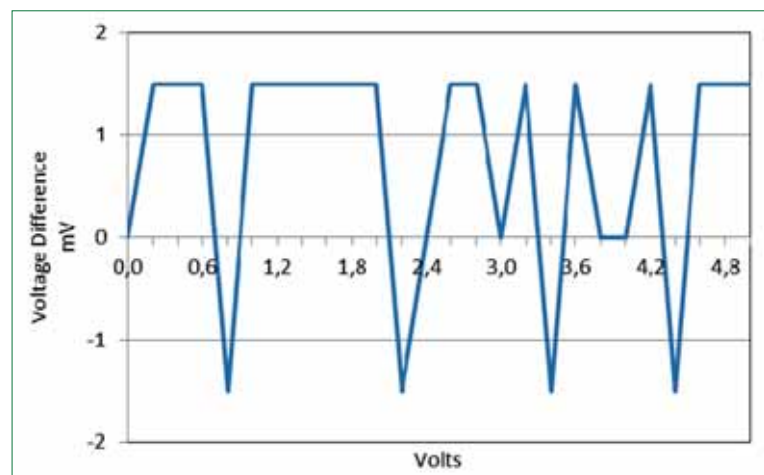


Fig. 5: Full range voltage test.

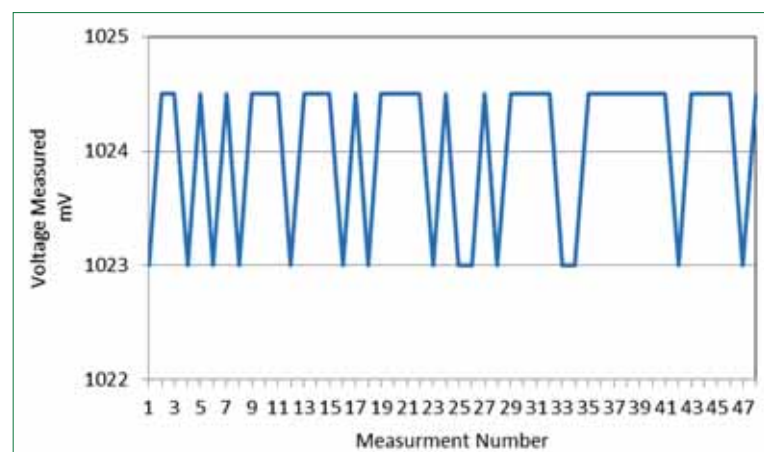


Fig. 6: Voltage tests at a stable voltage.

when using the DC-to-DC converter: Non-linear, vary with temperature, range limited at low voltages, require complex analogue multiplexers and accurate analog to digital conversions.

Of the four topologies covered thus far, three would have been suitable for accurate cell measuring systems. They

are the isolation amplifier, transformer isolation and the DC-to-DC converter. All of them had the necessary accuracy for cell measurement, but system integration was complex.

Simply put, these are the traditional methods of measuring voltages while incorporating galvanic isolation. IC

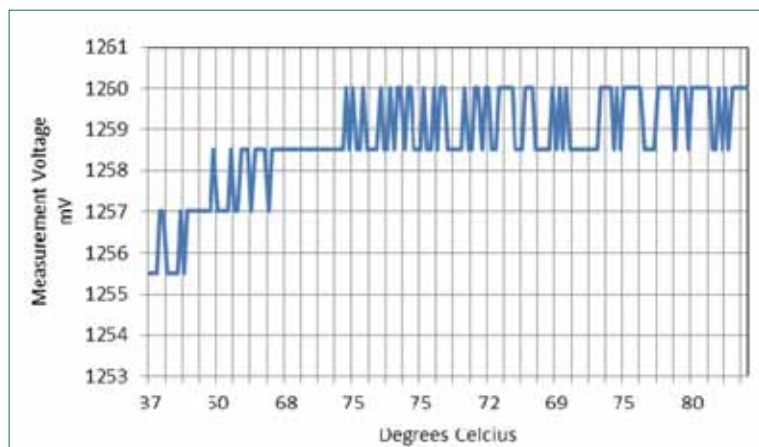


Fig. 7: Cell voltage change with an increase in chip temperature from 37 – 82°C.

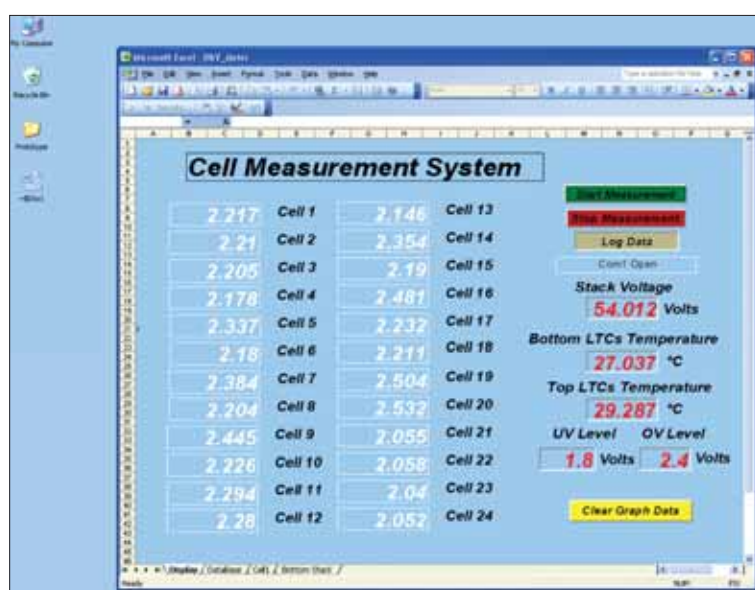


Fig. 8: Graphical user interface used to display cell information.

manufacturers realised this and saw that with the increasing use of cell stack application that a new method was needed to measure individual cells in large cell stacks in a small easily integrated package. They are battery management ICs and analysis on them follow in the next chapter.

The traditional methods used to create galvanic isolation did not provide adequate results. The methods were too inefficient and not accurate enough to be used. The methods that had the required accuracy were too complicated to connect in a useable system. Hence new ICs were developed by IC manufacturers and selected ones were investigated below

Stackable battery management ICs

A need for simpler, cheaper and a smaller way of battery management was needed. An IC allows all the necessary measurement hardware to be incorporated into a single small package. These ICs include all the required analogue multiplexers, analogue to digital converters

and voltage references for measurement of individual cells. Three ICs were chosen for investigation. They are the MAX11068 by Maxim, the ATA6780 by Atmel and the LTC6802-1 by Linear Technology Corporation.

From Table 2 it can be seen that the MAX11068 and the LTC6802-1 are very similar in their claimed results. The main differences are the analogue to digital converter used to acquire the cell voltages and the communication interface. The ATA6780 specification along with price made it uneconomical compared to the MAX11068 and the LTC6802-1. Availability and ease of obtaining the LTC made it the choice for the prototype board and all results shown will be for the LTC IC.

Test setup and procedure

To obtain twelve cells of different chemistries, or at least four, which is the minimum for the LTC IC, would have been costly. An adjustable cell simulator was thus developed to simulate the cells, and more specifically all the cell chemistry types.

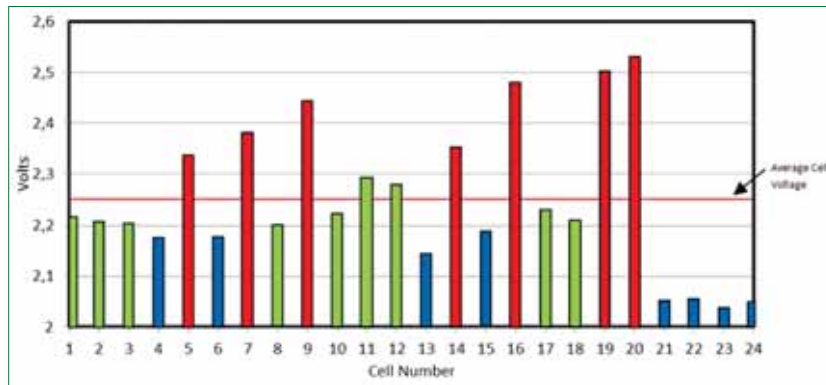


Fig. 9: Cell information captured from the actual lead acid battery stack.

Flowchart for microcontroller

An Atmel microcontroller was selected for the control of the ICs. The speed, peripherals as well as memory of the microcontroller were deemed adequate for a data acquisition interface.

The flowchart in Fig. 4 shows the program that was followed to obtain the cell measurements as well as do the other control.

Results

Full range voltage tests were done and the result can be seen in Fig. 5. The results show that there is a difference of 1,5 mV up or down from the actual voltage. This is well below the system specification and is considered accurate. The 1,5 mV deviation is from the resolution of the delta sigma ADC.

Fig. 5 was obtained by measuring the actual cell voltage with a five digit calibrated multimeter and subtracting the results from the measurement as obtained by the LTC IC. The voltage was adjusted from 0 – 5 V in 200 mV steps.

Fig. 6 was obtained in exactly the same way as the full voltage range tests. All cells were tested using this method and all results confirmed the results as shown above.

Heat tests for a single cell can be seen in Fig. 7. An oven with thermal control was used to slowly increase the heat to 50°C above ambient. This was done because the devices, under normal operation were just above 31 and 34°C respectively. Tests were done with the cell simulator as it was easier and safer to fit into the oven than a battery cell stack.

The LTC IC heat results are recorded onto the graph in Fig. 7. The results are that of the ADC and the internal temperature ADC of the LTC. From the graph above it can be seen that at a higher temperature the measured values were higher. The initial value was 1255 mV and changed to a maximum of 1260 mV. This is still within the system specification of <10 mV accuracy and that is after a total temperature change of more than 40°C.

After initial tests satisfied the accuracy of the measurement device, a lead acid series cell battery stack was connected and tests were done on that.

Fig. 8 shows the GUI used to interpret the data into organised, easily legible information. This information was updated after the readings were taken and logged for export.

The charger was set to deliver 2,25 V per cell which equates to 54 V and seen represented in Fig. 9 by the red line. The Undercharged cells can be seen in blue, the overcharged cells in red and the acceptable cells in green. This variation will increase with time and even at the current stage damages to cells will occur if charging and discharging is permitted.

The biggest difference for this stack is at cell 20 which is 282 mV above the ideal. This equates to a voltage of 2,532 V. If charging is permitted at this level the cell will fail prematurely as it has an elevated temperature and a loss of internal chemicals. The other end cell 23 has a voltage of 210 mV less than 2,25 V. This equates to a voltage of 2,04 V as can be seen on the GUI. At these low voltage levels the plates of the cells will sulphate, making them unusable over time. Having this information available there are three things that can be done:

When the stack is charged from a state where all the cells are below the ideal charging level of 2,25 V, the stack should only be charged until any cell reaches 2,25 V and then the charging should be stopped. This will undercharge most cells causing sulfation of the plates and future premature cell failure. When the cells are being discharged and the lowest cells voltage reaches 1,8 V the stack should be disconnected from the load. Since most of the cells were undercharged from the previous charge cycle this would occur much sooner than if all the cells were equal. Hence stack operating time is shortened.

Knowing that cell voltages are not equal they can be replaced with cells with similar voltage levels at the same SOC. This is

expensive, difficult and time consuming and will never work in reality.

Balancing can be incorporated to balance cells during the charging phase (active balancing could also be used during the discharge phase). Both passive and active balancing will ensure longer stack operation and cell lifetime at the cost of consuming some power.

Conclusion

The LTC IC was found to measure cell voltages with very good absolute and relative accuracy. Maximum deviation of any cell voltage when compared to measured cell voltage using a 5 digit calibrated voltmeter was 2 mV.

Maximum deviation with temperature variation from 24 to 75°C was 5 mV.

The chip was fairly easily stackable and the interface worked well. Chip cost at \$11,59 per 12 cells along with the printed circuit board, wiring and connections, fuse protection and environmental protection means that a cell voltage measuring system could be possibly be made for ± \$3 dollars per cell.

The GUI gives information on the 24 lead acid cells on an accessible interface. The individual cell information tells the users useful information on the stack. Even though alarms could be given through the GUI, hardware should have resolved any unfavorable condition before unnecessary damage is done to the equipment, cell stack or user.

References

- [1] J H Bergveld, "Battery management systems, design by modelling", PhD Thesis, Department of Electrical Engineering, University of Twente, ISBN 90-74445-51-9, Kluwer Academic Publishers, Netherlands, 2002.
- [2] B V Rathnakumar, and M C Smart, "Rechargeable Batteries", in M Broussely, G Pistoia (eds.), Industrial Applications of Batteries: From Cars to Aerospace and Energy Storage, 1st edn, Elsevier B.V., Netherland, 2007.
- [3] R Perez, "Lead Acid battery state of charge versus voltage", Home Power #36, August/September 1993, pp. 66-69, 1993.
- [4] J Stevens, and G Corey, "A study of lead acid battery efficiency near top of charge and the impact on PV system design", Unpublished Paper, Department of Battery Analysis and Evaluation, Sandia National Laboratories, New Mexico, 1998.
- [5] I De Vries, "Design considerations of active battery cell balancers", Unpublished Paper, Department of Electrical Engineering, Cape Peninsula University of Technology, Cape Town, 2008.
- [6] J Wagener, "Investigation and Design of a magnetically isolated DC-DC converter for use in cell balancing", A thesis in fulfillment of the requirements for the Magister Technologiae degree in Electrical Engineering, Department of Electrical Engineering, Cape Peninsula University of Technology, Cape Town, 2009.
- [7] M Williams, and J Thoren, "Novel measurement circuit eases battery-stack-cell design", EDN, 1 October 2008, pp. 53-63, 2008.

Contact Nick Prinsloo, Tel 076 043-5818, nickprinsloo@gmail.com or Dr. Ian de Vries, Tel 082 717-8389, ian.devries@gmail.com ♦