A Selective Voltage Measurement System for Series Connected Battery Packs

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Abstract

A method has been developed to measure the voltages of individual batteries used in hybrid electric vehicle (HEV) battery packs using a new selective battery measurement system. This system consists of a voltage measurement circuit that measures battery voltages using a set of electromechanical relays connected in a matrix formation. A sixteen-bit microcontroller was used for controlling the operation of the voltage measurement unit. The system was designed for a pack of twelve series connected 12V lead-acid batteries. The proposed method was found to be compact and is a universal one. Moreover, the set-up was very effective and produced good accuracy.

Key words - Hybrid electric vehicle, HEV, Voltage measurement, Lead-acid, Batteries.

1. Introduction

Several applications require the use of series connected battery packs for adequate power. These packs often need effective automated equipment to measure the battery voltages from time to time. The voltage is a good indicator of whether any battery is losing charge due to extraneous factors. Some of the factors that contribute towards reduction in life or charge retention of such batteries include the type of battery cell design, ambient temperature, and length of usage/storage [1,2]. This means that if there are certain subtle differences between the individual batteries, the batteries will not charge/discharge in a uniform manner. The result is that some units will be overcharged, some excessively discharged, and poor performance will result.

All batteries must remain within a high and low voltage operating range to prevent damage. During the discharge cycle, batteries which are less efficient tend to go out of voltage balance before the rest, resulting in an overall limiting of the total battery capacity. Similarly, during the charge cycle, batteries which are more efficient tend to get charged a little higher than the rest, resulting in an overcharge. Batteries that are overcharged are subject to an oxygen recombination cycle at their negative electrodes, and this causes their cycle life to be significantly reduced over a period of time [1,2]. Since the entire battery pack is exposed to a number of charge and discharge cycles, the after effect of these differences results in faster aging of the batteries due to overcharge and undercharge.

It is therefore imperative that battery voltage monitors must be accompanied with some type of equalization scheme to maintain voltage balance [3-8]. In fact, these systems combine to form battery management systems (BMSs) that monitor several critical battery parameters, such as the voltages and temperatures of individual batteries, and take corrective action whenever an imbalance arises in the battery pack [9]. The voltage measurements can be tricky because each measurement must be transferred from the battery pack to the ground reference used by the data processing system. Although this might seem to be a simplistic task, the system needs to obtain data quickly to prevent a catastrophic condition from occurring. High performance batteries such as lead-acid, lithium-ion and nickel metal hydride (NiMH) have higher energy densities, and therefore, they require precise monitoring to insure safety and performance.

2. Related work

There are several techniques to measure the battery voltages in series packs, the most evident method being using a resistive divider. Figure 1 shows such a circuit for twelve series connected batteries. The disadvantages for

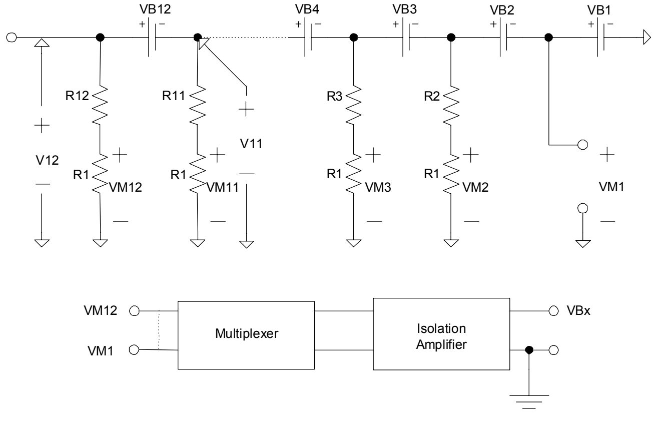


Figure 1. Resistive divider measurement

such a system are fairly clear. Firstly, switches must be provided to prevent the resistors from drawing current from the batteries when not in use. Secondly, the voltages near the top of the stack require very accurate (and expensive) divider ratios. For example, consider the top battery in a stack of twelve 12 V_{DC} batteries. Here, $K_{12} = R_1/(R_1+R_{12})$, $K_{11} = R_1/(R_1+R_{11})$ and so on. If the ideal values of K_{11} and K_{12} as defined in Figure 1 are, $K_{11} = 1/11$, $K_{12} = 1/12$,

$$V_{M11} = V_{11} \times K_{11} = 12V_{DC}, V_{11} = 132V_{DC} \tag{1}$$

$$V_{M12} = V_{12} \times K_{12} = 12V_{DC}, V_{12} = 144V_{DC} \tag{2}$$

$$V_{B12} = V_{12} - V_{11} = 12V_{DC} \tag{3}$$

However, if the actual K_{12} is in error by +1% and the actual K_{11} is in error by -1%, the actual $V_{12} = 145.44\ V_{DC}$, and $V_{11} = 130.68\ V_{DC}$.

Research has been performed to design transfer circuits using both bipolar junction transistors (BJTs) and operational amplifiers (op-amps) [10, 11]. Figure 2 shows a BJT transfer circuit that performs the required voltage shifting for measuring the segment voltages in a series battery pack. This circuit however requires the matching of several discrete components. The bipolar transistor circuits are inactive until Q_B is turned on, which provides a path for i_{E1} and i_{B2}. For V_{B3} to V_{Bn}, it can be shown that

$$V_M = \left(R_3 / R_2 \right) \times V_B \tag{4}$$

The diodes in the D_1 and D_2 positions are required to prevent leakage current that results from the reverse avalanche of the base to emitter junctions of the Q_1 transistors while the circuit is off, but they can be eliminated if V_{Bmax} is less than the V_{EB1} breakdown voltage. However, this means a diode would have to be placed in series with each R_1 (except the one for V_{Bn}) to prevent breakdown and the resulting leakage caused by battery segments to the left. If V_{B1} is <5 V_{DC}, it can be measured directly as shown with a standard A/D converter. For higher voltages, a resistive divider similar to that for V_{B2} can be used for V_{B1}. Q_A prevents leakage current in the off state and its saturated R_{dson} is negligible compared to R_4 and R_5. If each V_M is processed by a microcontroller, initial tolerances can be reduced considerably, by using a calibrated test fixture and storing a correction factor in flash memory for each V_M. Although initial tolerance errors can be reduced to a very low-level, temperature induced variations prove to be more difficult. For example [11] presents data showing how temperature variations may create variations in 'β' that affect the measurement values. 'β' effects can be reduced by replacing Q_1 and Q_2 with Darlington pairs, but this probably means almost twice the number of discrete transistors since the selection of small surface mount Darlington pairs is very limited. Variations in component matching also may increase as more parts are added.

Transfer circuits using op-amps have been found to have several advantages, however, they face severe leakage issues and additional circuitry is therefore required which increases their cost [11]. These circuits are well suited to lithium-ion batteries that will ignite if accidentally overcharged and this necessitates such extremely accurate voltage measurements for each cell. Lead-acid and NiMH batteries also have maximum voltage limits that should be observed, but the issue here is a decrease in lifetime instead of an abrupt ignition. Therefore, monitoring of several cells together is usually adequate, such as the common practice of measuring a segment of six 2 V cells for lead-acid batteries. Since voltage accuracy is not as critical for these batteries as for lithium-ion, the op-amp version is not suitable. While the discrete BJT version is probably satisfactory, its disadvantages noted in this section prove detrimental if the pack is used in conditions that have extreme temperature fluctuations.

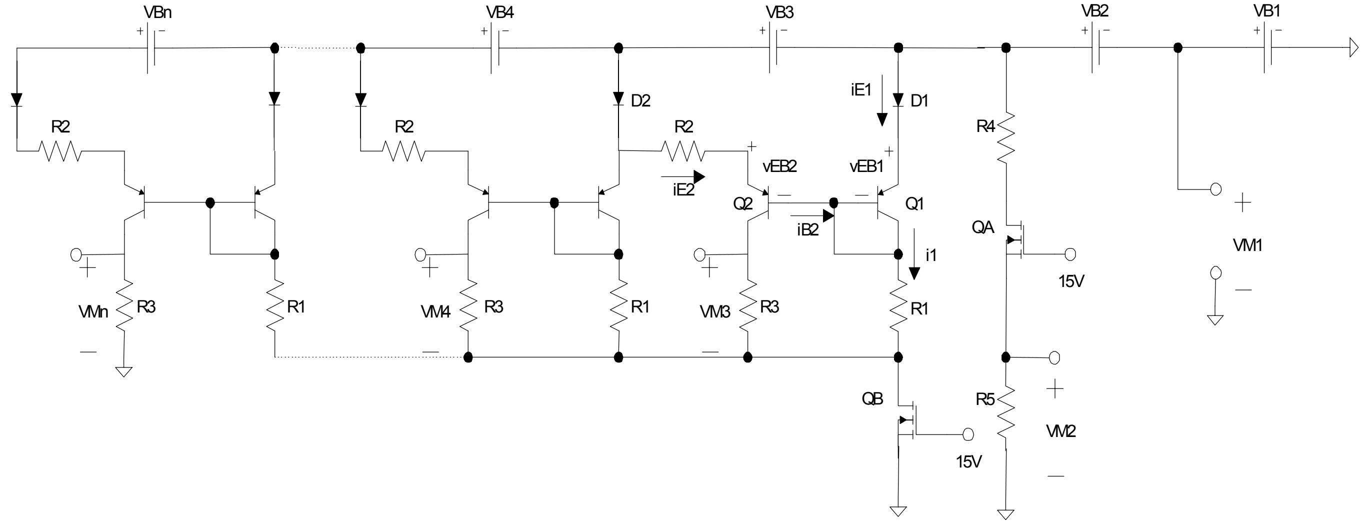


Figure 2. Transfer circuit with BJTs

3. The selective voltage measurement unit

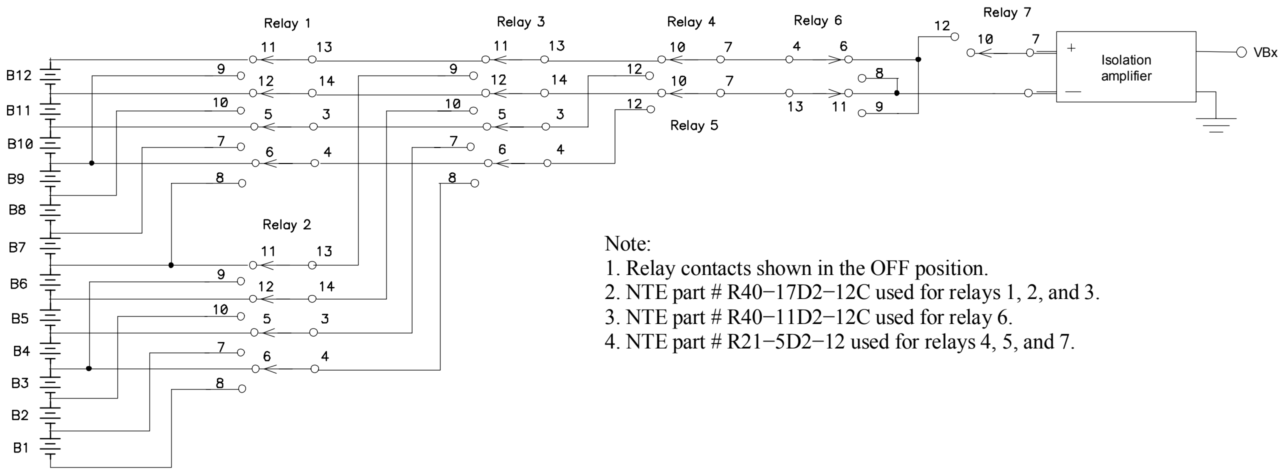
The proposed voltage measurement circuit uses NTE electromechanical relays [12,13] to access a particular battery for voltage measurement. This circuit was tested on twelve series connected $12V_{DC}$ EnerSys Genesis G13EP lead-acid batteries (B_1 - B_{12}) rated at 13 Ah [14]. A sixteen-bit Motorola MC68HC812A4 microcontroller [15] was used to implement the above tasks. One isolation amplifier was used to route the selected battery voltage to the microcontroller analog-to-digital converter. The microcontroller selects each battery individually in a cyclic manner. In order to select a battery for voltage measurement, a digital signal is sent from the microcontroller I/O port to a control logic interface circuit. This signal represents a number that indicates the battery selected for measurement. The control logic interface circuit decodes the signal and turns on the required relays in a relay matrix module to select the required battery.

Figure 3 shows the relay matrix module that comprises of seven relays, and Figure 4 shows the control logic interface module consisting of a set of FETs (Q_1 – Q_7), two latches, and eight NAND gates. PH0-PH5 (Port H of microcontroller) was used to output a 6-bit binary number that represents the battery whose voltage is required to be measured. Table 1 shows the binary numbers for each of the twelve batteries. For example, in order to measure the voltage of battery B_7, the 6-bit data output from PH0-PH5 of the microcontroller corresponds to 100111_2 (in binary). This data is then latched onto the outputs of the two CD4042 latches causing field effect transistors (FETs) Q_1, Q_4, Q_5, and Q_7 to turn ON. Therefore, relays 1, 4, 5, and 7 turn ON, and B_7 is connected to the input of the isolation amplifier for measurement. Relays 1, 2, 3, 4, and 7 were driven by signals directly from PH0, PH1, PH2, PH3, and PH5 respectively. However, relays 5 and 6 were controlled by a set of NAND gates in conjunction with microcontroller signals PH3 and PH4. This was done in order to perform the function of reversing the polarity for batteries B_2, B_5, B_8, and B_{11}, so that the positive terminals of these batteries are connected to the positive terminal of the isolation amplifier whenever any one of these is selected for a measurement.

An Axiom MC68HC812A4 development board [16] was used for the implementation of the measurement circuit. Although a smaller eight-bit microcontroller such as the Motorola MC68HC11 could have been used for the system to save cost, the sixteen-bit MC68HC812A4 was chosen because the development board was being used in the curriculum and was readily available for use. The circuit was fairly inexpensive with the major cost components comprising of the isolation amplifier and microcontroller. An Analog Devices 5B41-07 isolation amplifier [17] was used to implement the galvanic isolation in the circuit. The isolation amplifier had a fairly low current consumption and was rated for a temperature range of -40 to 85^{o}C while each of the NTE relays were rated for a temperature range of -40 to 65^{o}C. This implies that the system as a whole is quite robust and reliable under severe environmental conditions. The experimental results documented in the next section were quite encouraging.

4. Experimental results

Sample and hold circuits were not required for these tests because there was no significant battery current. The MC68HC812A4 microcontroller was used as the CPU of the measurement system. It possessed an eight-bit A/D converter for digitizing the input analog voltages. The microcontroller in this system measures the twelve voltages every 10 sec and sends the results via a serial RS232 link to a PC for display and storage. The HyperTerminal program was used to display the data on the PC.



Note:
1. Relay contacts shown in the OFF position.
2. NTE part # R40−17D2−12C used for relays 1, 2, and 3.
3. NTE part # R40−11D2−12C used for relay 6.
4. NTE part # R21−5D2−12 used for relays 4, 5, and 7.

Figure 3. Relay matrix transfer circuit

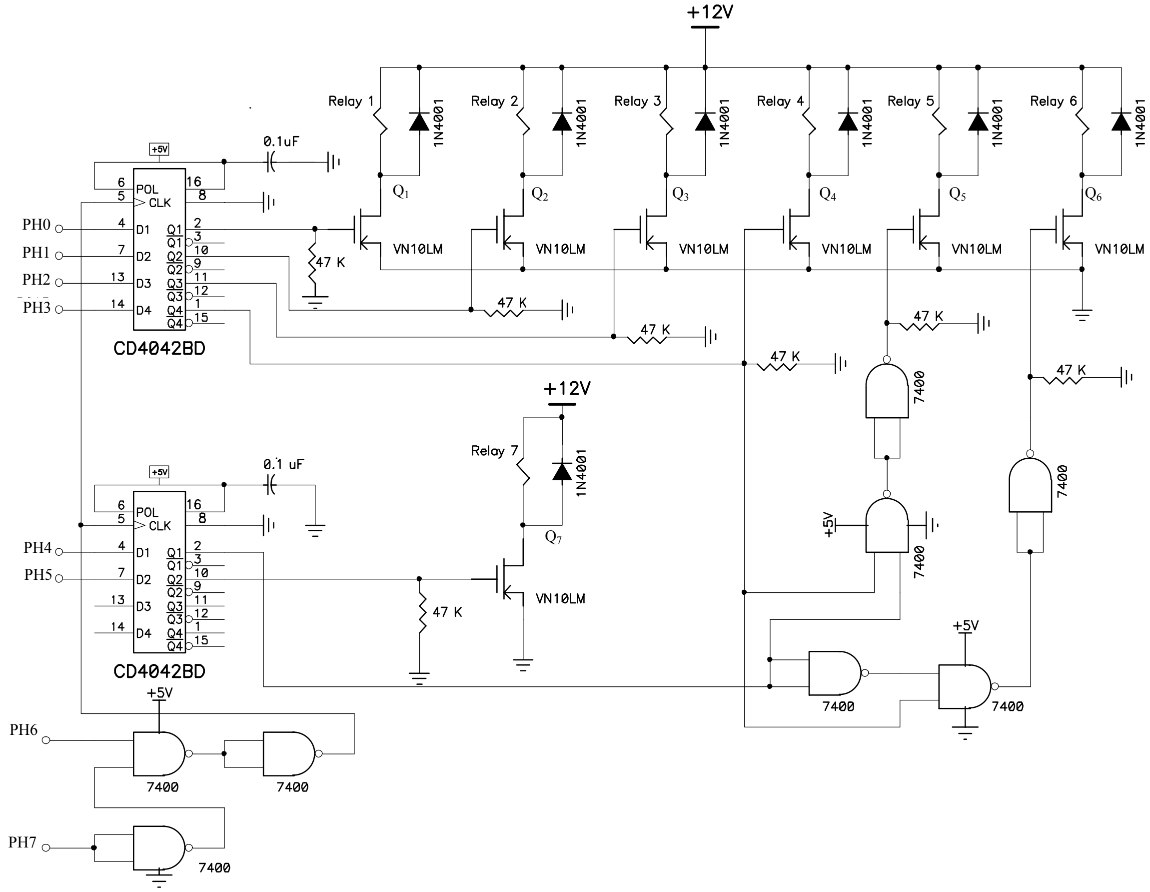


Figure 4. Control circuit for the relay

Table 1. Logic table for battery

Battery	PH0	PH1	PH2	PH3	PH4	PH5
B_{12}	0	0	0	0	0	1
B_{11}	0	0	0	1	0	1
B_{10}	0	0	0	1	1	1
B_9	1	0	0	0	0	1
B_8	1	0	0	1	0	1
B_7	1	0	0	1	1	1
B_6	0	0	1	0	0	1
B_5	0	0	1	1	0	1
B_4	0	0	1	1	1	1
B_3	0	1	1	0	0	1
B_2	0	1	1	1	0	1
B_1	0	1	1	1	1	1

Table 2 and 3 compare the circuit measurements (Measured) with digital voltmeter measurements taken directly at the battery terminals (Actual). These results indicate a maximum error of ± 0.3 %. These tolerance errors were eliminated using an automated calibration procedure which is discussed later. Although the results in Table 2 are considered satisfactory, it is of interest to note that the eight-bit A/D measurements itself would have a maximum truncation error of approximately ± 20 mV. On average, detailed measurements could only account for about an additional error of 20 mV. Although these initial tolerances would be adequate for many applications, initial calibration could easily reduce these tolerances to less than ± 0.2 % with precise reference voltages and correction factors in flash memory. This can be done using an automated procedure which is presently under

Table 2. Initial battery voltage measurements

	Measured	Actual
B1	12.62	12.59
B2	12.65	12.62
B3	12.56	12.60
B4	12.60	12.63
B5	12.58	12.61
B6	12.57	12.60
B7	12.56	12.60
B8	12.59	12.63
B9	12.60	12.63
B10	12.59	12.62
B11	12.57	12.61
B12	12.51	12.55

Table 3. Initial battery voltage tolerances

	mV Differential	% Difference
B1	30	0.23 %
B2	30	0.23 %
B3	-40	-0.31 %
B4	-30	-0.23 %
B5	-30	-0.23 %
B6	-30	-0.23 %
B7	-40	-0.31 %
B8	-40	-0.31 %
B9	-30	-0.23 %
B10	-30	-0.23 %
B11	-40	-0.31 %
B12	-40	-0.31 %

Table 4. Measurement variation due to temperature above 20°C

	20°C	30°C	40°C
B1	12.62	12.62	12.62
B2	12.64	12.64	12.64
B3	12.56	12.57	12.57
B4	12.62	12.62	12.62
B5	12.60	12.61	12.60
B6	12.57	12.58	12.59
B7	12.58	12.59	12.59
B8	12.61	12.60	12.61
B9	12.61	12.60	12.60
B10	12.59	12.59	12.59
B11	12.60	12.60	12.60
B12	12.61	12.61	12.61

Table 5. Measurement variation due to temperature below 20°C

	-20°C	-10°C	0°C	10°C	20°C
B1	12.59	12.59	12.59	12.59	12.59
B2	12.60	12.60	12.61	12.60	12.61
B3	12.50	12.51	12.51	12.52	12.52
B4	12.56	12.57	12.57	12.58	12.59
B5	12.55	12.55	12.56	12.57	12.57
B6	12.51	12.53	12.53	12.53	12.54
B7	12.44	12.46	12.46	12.46	12.47
B8	12.55	12.55	12.56	12.56	12.57
B9	12.55	12.55	12.56	12.55	12.57
B10	12.53	12.53	12.53	12.54	12.54
B11	12.55	12.55	12.56	12.57	12.56
B12	12.52	12.53	12.54	12.54	12.55

development.

The circuit performance was examined over a temperature range of -20°C to 40°C. During each temperature test, the circuit was allowed to "soak" for at least four hours at each temperature level in order to establish thermal equilibrium.

The batteries themselves were always kept at 20°C since only circuit-induced measurement errors were of interest. Table 4 shows the voltage measurement variations for the 20-40°C temperature range. It can be observed from Table 4 that the fluctuations in voltage measurement were minimal in the 20-40°C temperature range. In fact, the worst case deviation was only ± 20 mV for battery B_6. The measurement deviations for the rest of the batteries were within ± 10 mV.

Table 5 shows the measurement deviation for temperatures below 20°C. It can be seen that the worst case B_4, B_6, and B_{12} varied only ± 30 mV over the temperature 20 to -20°C temperature range. It should be noted that the battery voltages at 20°C in Table 5 are slightly lower than those at 20°C in Table 4 due to the voltages drifting over time between the start of each set of measurements. This drift with time also can have a slight affect on the measurements while the experiment is in progress.

The deviation in the B_4, B_6, and B_{12} voltage measurement is shown in Figure 5 with respect to the initial value at 20°C. The values on the y-axis are the difference in voltage measurements with respect to the corresponding 20°C voltage measurement. For example, the y-axis values for B_4 are calculated as follows,

$$\Delta V_4 = V_{B4-T} - V_{B4-20} \tag{5}$$

where: $V_{B4\text{-}T} = V_{B4}$ @ the specified temperature and
$V_{B4\text{-}20} = V_{B4}$ @20°C.

It can be observed from Figure 5 that as the ambient temperature decreases, the monitor measurements tend to decrease. This is probably a result of the temperature effect on the relay contact resistance which tends to increase with a decrease in ambient temperature.

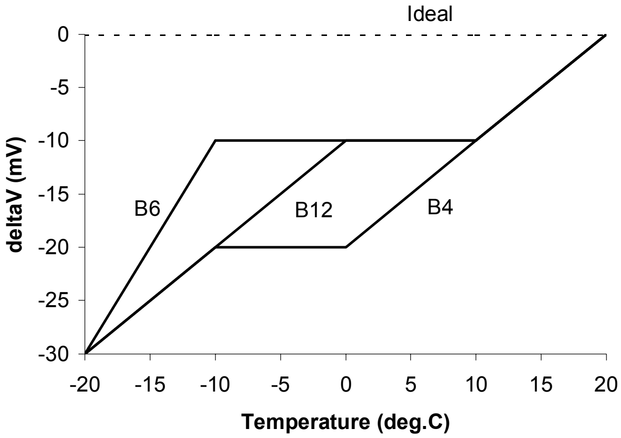


Figure 5. B_4, B_6, and B_{12} results for the -20 to 20°C range

5. Conclusions

The new selective voltage measurement circuit proved to be very effective for measuring the twelve series connected lead-acid battery voltages. The technique used for measurement is a universal one and is not restricted to one particular type of battery. This is because the measurement principle simply selects batteries for voltage measurement in a cyclic manner. Several tests were carried out in order to evaluate the voltage measurement circuit. Experimental results indicate that the circuit can achieve reasonable accuracy without the need for high precision components. Even without initial calibration, a ± 0.3% maximum error was achieved, and temperature variations were less than ± 30 mV over a temperature range of -20 to +40°C.

The circuit is compact and makes use of inexpensive components. Moreover, it can be broken down into modularized units located close to the batteries so that each unit serves a particular section of the battery pack. Since applications such as electric and hybrid electric vehicles require several series connected batteries for propulsion, these modularized versions [9] are probably the best choice for future implementation. The lifetime of relays used was rated at a minimum of 3 x 10^5 switching operations at a relatively high power rating of 2 A_{DC}, 30 V_{DC} [12,13]. This indicates that the circuit should have a fairly long life.

6. Acknowledgements

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