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An electromechanical transfer circuit to measure individual battery voltages in series packs

Abhiman Hande[a,*], Sukumar Kamalasadan[b]

[a] Erik Jonsson School of Engineering and CS, University of Texas at Dallas, P.O. Box 830688, EC33, Richardson, TX 75083, United States
[b] Division of Engineering and Computer Technology, University of West Florida, Building 77, Room 131F, Pensacola, FL 32514, United States

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Abstract

A novel approach has been developed to measure the voltages of individual batteries used in electric vehicle (EV) battery packs using a unique 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 16-bit microcontroller was used for controlling the operation of the relay matrix circuit. The system was designed for a pack of 12 series connected 12 V_{dc} lead–acid batteries. The proposed approach was found to be compact and is a universal one that can be used for any type of battery. Moreover, the method was very effective and produced good accuracy. In fact, test results over a wide temperature range of −20 to +40 °C indicated that the method is very precise with voltage fluctuations less than ±30 mV.

Keywords: Electric vehicle; Voltage measurement; Lead–acid; Batteries; Relays

1. Introduction

Several applications such as electric vehicles and uninterruptible power supplies require the use of series connected battery packs for adequate power. These packs often need precise and autonomous voltage measuring schemes for accurate battery voltage measurements from time to time. The battery 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 battery life or charge retention 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 individual batteries in a pack, the batteries will not charge/discharge in a uniform manner, resulting in overcharge and excessive discharge in some units.

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. This phenomenon limits the total battery capacity. Also, during the charge cycle, batteries which are more efficient tend to get charged a little higher than the rest, resulting in an overcharge. Batteries such as nickel metal hydride (NiMH) and lead–acid when 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].

It is possible to obtain a fair idea of the state of health of a battery by keeping track of its terminal voltage. For example, the open circuit voltage (OCV) and state of charge (SOC) for a 12 V_{dc}, 13 ampere-hour (Ah) EnerSys Genesis G13EP lead–acid battery have the following linear relationship for the 10–100% SOC range [16]:

$$\mathrm{SOC} = \frac{\mathrm{OCV} - 11.6}{0.0126} \tag{1}$$

Therefore, the SOC of each battery in series connected packs can easily be predicted by measuring its terminal voltage after some period of time at rest. This information is used to identify weak batteries so that they can receive an additional boost charge to balance the pack. It is therefore imperative that battery voltage monitors 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 volt-

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[*] Corresponding author. Tel.: +1 972 883 6563; fax: +1 972 883 2710.
E-mail addresses: abhiman.hande@utdallas.edu (A. Hande), skamalasadan@uwf.edu (S. Kamalasadan).

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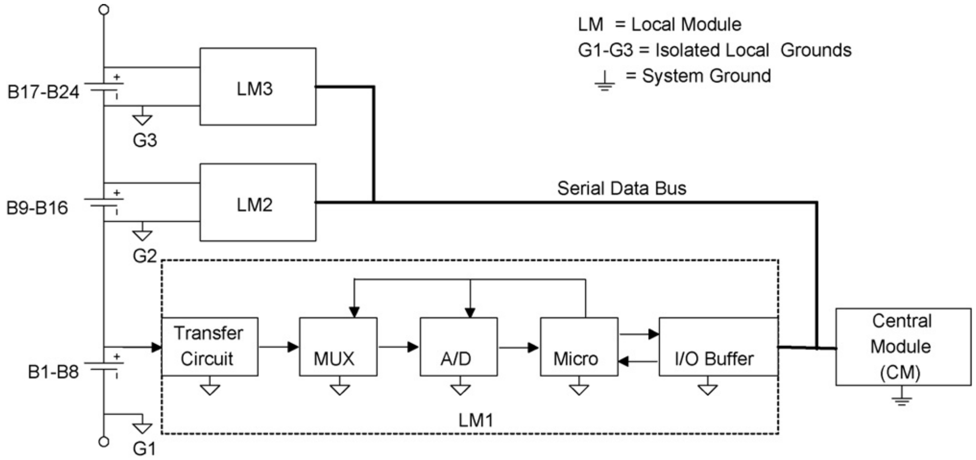


Fig. 1. Modular battery management system.

ages and temperatures of individual batteries, and take corrective action whenever an imbalance arises in the battery pack [9,10]. Fig. 1 shows a typical modular battery management system that consists of several local modules (LMs) each catering to the need of a well-defined section of the battery pack. In this case, each LM monitors eight batteries and consists of several key components that include a transfer circuit, multiplexer, analog-to-digital (A/D) converter, microcontroller, and an input–output (I/O) buffer. A serial data link provides communication between each LM and a common central module (CM). The CM commands all LMs to simultaneously measure and store their battery voltages locally, and the results are then sequentially transmitted to the CM. It is apparent that the transfer circuit is one of the important elements in each LM and thus, needs special attention in design and development. In fact, these voltage measurements can be quite tricky because each measurement must be transferred from the battery pack to the ground reference used by the data processing system as shown in Fig. 2. 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 NiMH have higher energy densities, and therefore, they require precise monitoring to ensure safety and performance.

There are several techniques to measure the battery voltages in series packs, the most evident method being using a resistive divider. Fig. 3 shows such a circuit for 12 series connected batteries. The disadvantages for 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 12 12 $\mathrm{V_{dc}}$ 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 Fig. 3 are, $K_{11} = 1/11$ and $K_{12}=1/12$

$$V_{\mathrm{M}_{11}} = V_{11} \times K_{11} = 12\,\mathrm{V_{dc}}, \quad V_{11} = 132\,\mathrm{V_{dc}} \tag{2}$$

$$V_{\mathrm{M}_{12}} = V_{12} \times K_{12} = 12\,\mathrm{V_{dc}}, \quad V_{12} = 144\,\mathrm{V_{dc}} \tag{3}$$

$$V_{\mathrm{B}_{12}} = V_{12} - V_{11} = 12\,\mathrm{V_{dc}} \tag{4}$$

However, if the actual K_{12} is in error by +1% and the actual K_{11} is in error by −1%, the actual $V_{12} = 145.44\,\mathrm{V_{dc}}$, and $V_{11} = 130.68\,\mathrm{V_{dc}}$. This would mean that the measured $V_{\mathrm{B}_{12}}$ equals 14.76 $\mathrm{V_{dc}}$, instead of 12 $\mathrm{V_{dc}}$ (an error of 23%).

Another obvious method is to simply provide each battery with its own isolation amplifier [11]. The isolation amplifier shifts the battery voltages to the common reference, and the accuracy problems related to resistive dividers are avoided. A typical circuit is shown in Fig. 4, where the individual V_{B_x} can be multiplexed as in Fig. 3. Sample and hold circuits also can be added to both Figs. 3 and 4 to provide a simultaneous measurement scan. This system meets the necessary accuracy requirements,

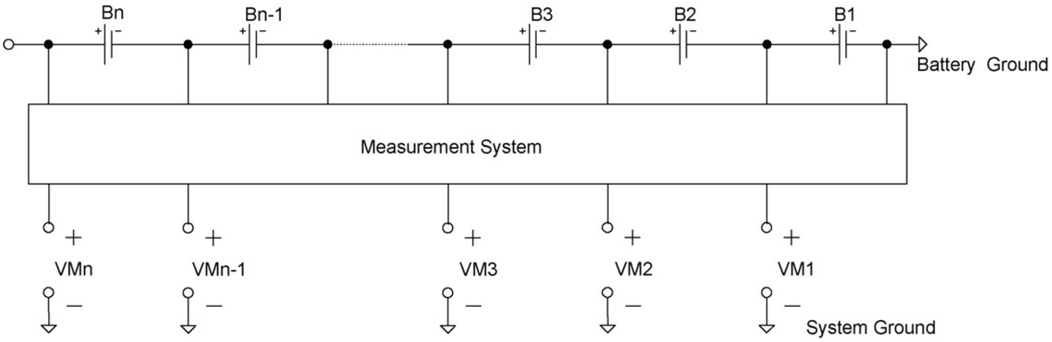


Fig. 2. Typical voltage measurement system.

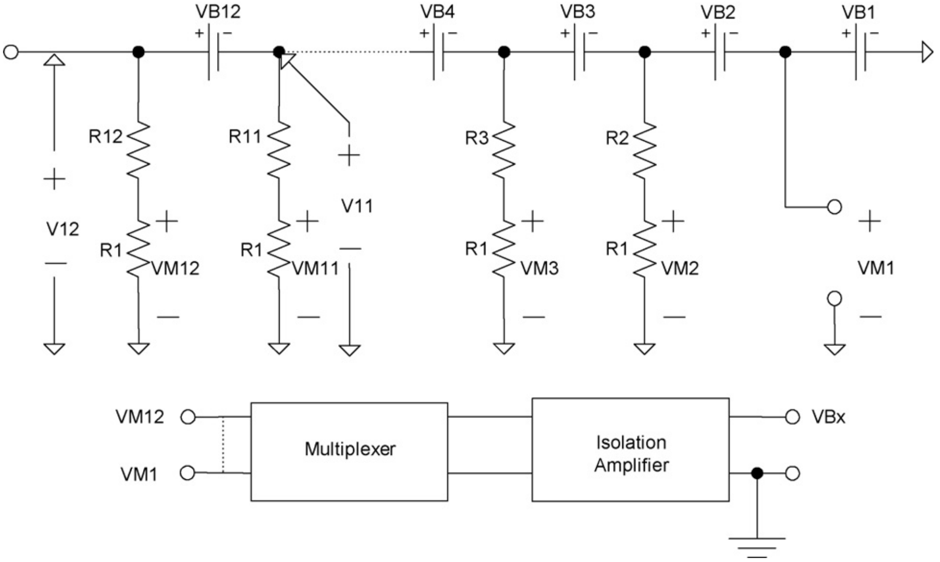


Fig. 3. Resistive divider measurement.

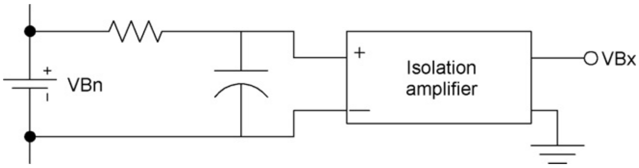


Fig. 4. Individual isolation amplifier measurement system.

but it is physically large and expensive due to the high cost of the amplifiers. A different method that is commercially available uses localized data processing. Exact details are usually proprietary, but a typical system can be implemented with a circuit similar to Fig. 5. In this type of system, each battery has its own microcontroller, including an A/D converter and a galvanically isolated serial port. The serial data link provides communication between each microcontroller and a common central processing unit similar to the CM in Fig. 1. Although technically feasible, these systems are still relatively expensive.

2. Related work and proposed approach

This paper looks into the feasibility of using small telecommunication electromechanical relays in a unique matrix formation to acquire voltage measurements from each battery in series packs. The motivation for exploring this approach stems from a similar circuit that was earlier used as an equalizer to boost weak batteries in series NiMH packs [8]. Another version of this circuit used solid-state relays in a matrix formation for trickle charging weak batteries in a lithium-ion pack that consisted of 4 V_{dc} cells [9,10]. The present work builds on these earlier equalizers by using different circuit components including relays, microcontroller, interface components, and a new algorithm for voltage measurement and display. Also, this work is more inclined towards 12 V_{dc} lead–acid batteries rather than NiMH or lithium-ion batteries.

Research work in this direction evolved from the idea that transfer circuits using both bipolar junction transistors (BJTs) and operational amplifiers (op-amps) [12,13] can be used to measure individual battery voltages in series packs. Garrett and Stuart [12] describes a BJT transfer circuit that provides the required voltage shifting for measuring the segment voltages in a series battery pack. This circuit, however, requires the matching of several discrete components. Here, each voltage measurement can be processed by a microcontroller and the initial tolerances can be reduced considerably by using correction factors in flash memory for each measurement. But temperature induced variations prove to be more difficult to solve. For example Garrett and Stuart [12] presents data showing how temperature variations

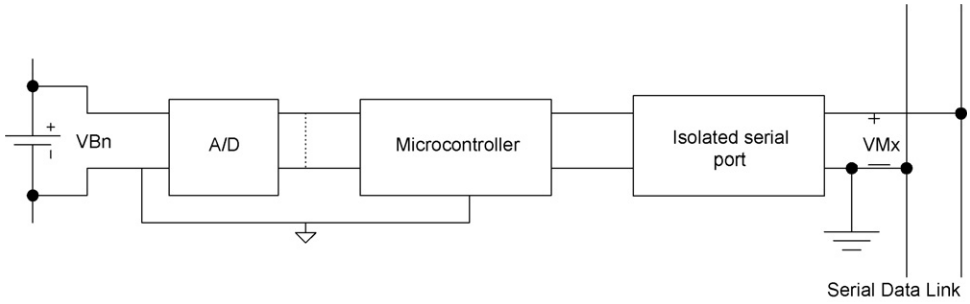
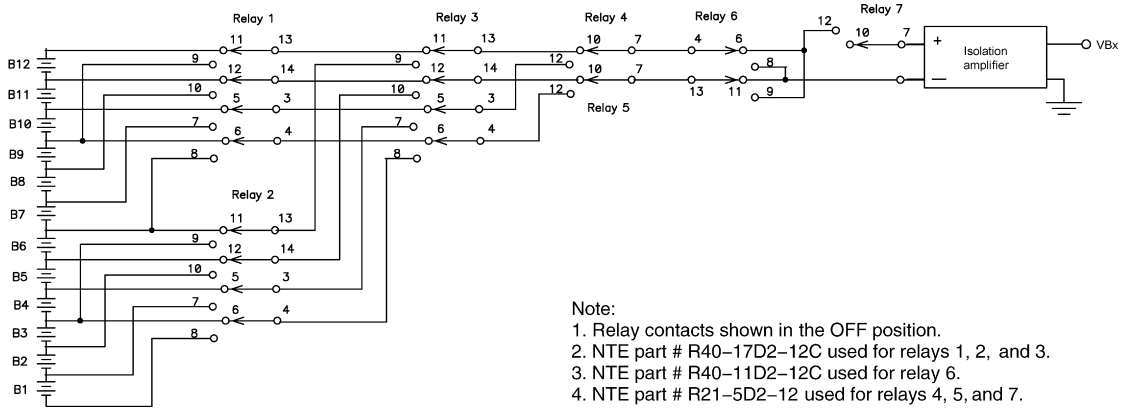


Fig. 5. Localized data processing measurement system.



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.

Fig. 6. Relay matrix transfer circuit.

may create variations in ‘β’ that affect the measurement values. ‘β’ effects can be reduced by using BJTs in 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 provide extremely accurate measurements. However, they face severe leakage issues and additional circuitry is therefore required which increases their cost [13]. These circuits are well suited to lithium-ion batteries that can experience thermal runaway 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 thermal runaway. Therefore, monitoring of several cells together is usually adequate, such as the common practice of measuring a segment of six 2 V_{dc} cells for lead–acid batteries. Since voltage accuracy is not as critical for these batteries, it turns out to be impractical to use the complicated and expensive op-amp transfer circuit here. 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. The disadvantages of previous measurement techniques for monitoring voltages of lead–acid and NiMH batteries calls for investigating additional methods towards designing transfer circuits. Thus, in this paper the main objective is to develop a novel approach using a relay matrix transfer circuit and controller that can be used for effective voltage measurement. The proposed approach looks into a design that overcomes the deficiencies of the circuits that have been developed till date.

2.1. Relay matrix transfer circuit and control interface

The proposed voltage measurement circuit uses NTE electromechanical relays [14,15] to access a particular battery for voltage measurement. A 16-bit Motorola MC68HC812A4 microcontroller [17] was used to implement the prescribed tasks. One isolation amplifier was used to route the selected battery voltage to the microcontroller A/D 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. This circuit was tested on 12 series connected 12 V_{dc} EnerSys Genesis G13EP lead–acid batteries (B_1–B_{12}) rated at 13 Ah [16].

Fig. 6 shows the relay matrix module that comprises of seven relays, and Fig. 7 shows the control logic interface module consisting of a set of FETs (Q_1–Q_7), two latches, and eight NAND gates. PH_0–PH_5 (Port H of microcontroller) was used to output a six-bit binary number that represents the battery whose voltage is required to be measured. Table 1 shows the binary numbers for each of the 12 batteries. For example, in order to measure the voltage of battery B_5, the six-bit data output from PH_0–PH_5 of the microcontroller corresponds to 001101_2 (in binary). This data is then latched onto the outputs of the two CD4042 latches causing field effect transistors (FETs) Q_3, Q_4, Q_6, and Q_7 to turn ON. Therefore, relays 3, 4, 6, and 7 turn ON, and B_5 is connected to the input of the isolation amplifier for measurement. Table 2 shows the relays that turn ON when any of the 12 batteries is selected for measurement. Relays 1, 2, 3, 4, and 7 were driven by signals directly from PH_0, PH_1, PH_2, PH_3, and

Table 1
Logic table for battery selection

Battery	PH_0	PH_1	PH_2	PH_3	PH_4	PH_5
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

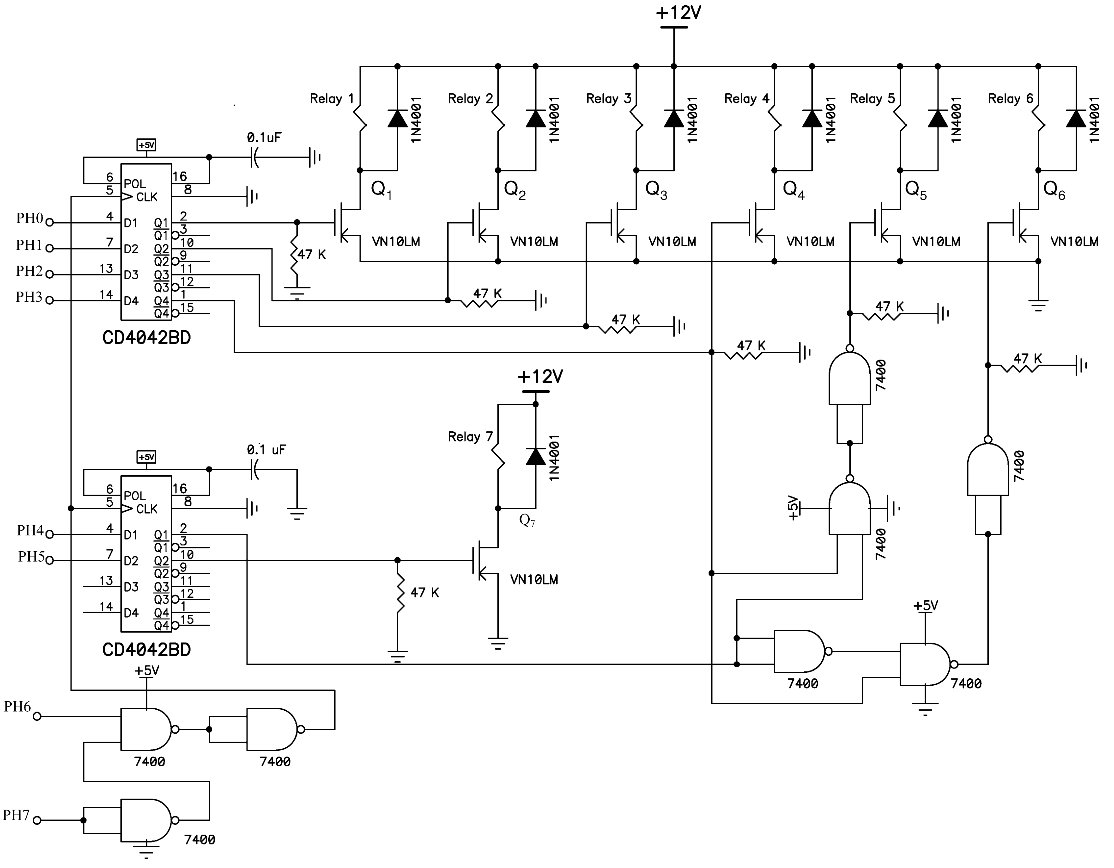


Fig. 7. Control circuit for the relay matrix.

PH$_5$, respectively. However, relays 5 and 6 were controlled by a set of NAND gates in conjunction with microcontroller signals PH$_3$ and PH$_4$. 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 [18] 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 16-bit MC68HC812A4 was chosen because the development board 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 [19] was used to implement the galvanic isolation in the circuit. This device had an input voltage specification in the 0–20 V$_{dc}$ range and therefore, the battery selected for measurement can be directly connected to its input terminals. It was also rated to provide an output voltage equal to its input voltage scaled down by a factor of four. This implies an output voltage in the 0–5 V$_{dc}$ range that can be directly applied to the microcontroller A/D input since the microcontroller operates at 5 V$_{dc}$. The isolation amplifier had a reasonably low current consumption and was rated for a temperature range of −40 to 85 °C while each of the NTE relays were rated for a temperature range of −40 to 65 °C. This implies that the system as a whole is quite robust and reliable under severe environmental conditions.

However, there are a few drawbacks that are worth highlighting at the outset. If relays 1, 2, or 3 are stuck in either the ON or OFF position, the system will measure a different battery voltage. For example, if relay 1 is stuck in its ON position, B$_9$ will be measured instead of B$_{12}$, B$_8$ will be measured instead of B$_{11}$, and B$_7$ will be measured instead of B$_{10}$. The situation is more grave if relays 4 or 5 misbehave. For example, in the case of B$_8$ measurement, if relays 4 and 5 are stuck in their OFF positions, a

Table 2
Logic table for relay selection

Battery	Relay 1	Relay 2	Relay 3	Relay 4	Relay 5	Relay 6	Relay 7
B$_{12}$	0	0	0	0	0	0	1
B$_{11}$	0	0	0	1	0	1	1
B$_{10}$	0	0	0	1	1	0	1
B$_9$	1	0	0	0	0	0	1
B$_8$	1	0	0	1	0	1	1
B$_7$	1	0	0	1	1	0	1
B$_6$	0	0	1	0	0	0	1
B$_5$	0	0	1	1	0	1	1
B$_4$	0	0	1	1	1	0	1
B$_3$	0	1	1	0	0	0	1
B$_2$	0	1	1	1	0	1	1
B$_1$	0	1	1	1	1	0	1

negative voltage in the 40–50 V_{dc} range will appear at the input of the isolation amplifier and undoubtedly damage it. Similarly, if relay 6 is stuck in its OFF position and fails to reverse polarity for B_2, B_5, B_8, and B_{11}, a negative voltage in the range of 10–13 V_{dc} will appear at input of the isolation amplifier. This will not damage the amplifier because it is rated for a ±20 V_{dc} input voltage, but a negative voltage in the 0–5 V_{dc} range will be outputted to the microcontroller A/D input instead of a positive 0–5 V_{dc} output. However, the authors have not experienced any inadvertent relay failure during their tests so far and do not anticipate failure until the relays have reached their maximum lifetime. The experimental results are documented in the next section.

3. Experimental results and discussion

The MC68HC812A4 microcontroller was used as the central processing unit (CPU) of the measurement system. It possessed an eight-bit A/D converter for digitizing the input analog voltage. The microcontroller in this system measures the 12 voltages and sends the results every 10 s via a serial RS232 link to a PC for display and storage. Fig. 8 shows the algorithm used for executing each measurement scan. After initializing the system parameters at start-up, the microcontroller selects B_1 for measurement by sending 0111111_2 (in binary) from Port H. This causes relays 2, 3, 4, 5, and 7 to turn ON, and the measurement is stored in a buffer. Next, the battery number is incremented and B_2's voltage is measured. This process continues until the voltage of B_{12} is measured. After obtaining the 12 voltage measurements, they are sent to a PC for display via an RS232 link. The microcontroller is then forced into a low power sleep mode for about 9 s to minimize power consumption. Here, an asynchronous timer is invoked that generates an internal interrupt to wake the microcontroller after 9 s. After waking up, the above steps are repeated to obtain another measurement scan. The HyperTerminal program was used to display the data on the PC.

A complete voltage scan time for the 12 batteries was about 600 ms. This relatively high value was due to a deliberate 50 ms delay after each battery voltage measurement. This relatively conservative delay was inserted to account for the contact bouncing in the relays during each battery voltage measurement and it can be reduced if necessary. Recent tests, however, have shown that anything less than 10 ms per voltage measurement is not feasible for the present design. This indicates a best case total scan time of 120 ms for all 12 measurements. In order to reduce the scan time even further, other types of relays will be explored in the near future. In the present set-up, the 9 s sleep time along with the voltage scan time, crystal oscillator wake up time, serial transmission delay, and other circuit delays accounted for a total of ten seconds per voltage scan.

Table 3 compares the circuit measurements (measured) with digital voltmeter measurements taken directly at the battery terminals (actual). These results indicate a maximum error of ±0.3%. Although the results in Table 3 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

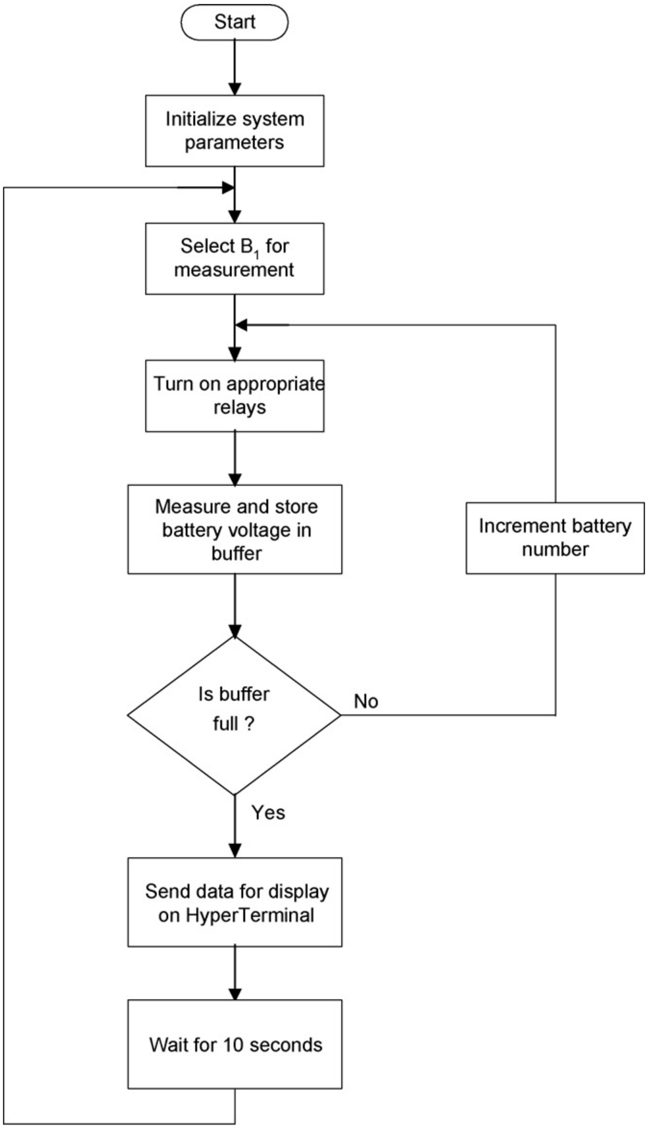


Fig. 8. Voltage measurement algorithm.

Table 3
Initial battery voltage measurements

Battery	Measured	Actual	Differential (mV)	Difference (%)
B_1	12.62	12.59	30	0.23
B_2	12.65	12.62	30	0.23
B_3	12.56	12.60	−40	−0.31
B_4	12.60	12.63	−30	−0.23
B_5	12.58	12.61	−30	−0.23
B_6	12.57	12.60	−30	−0.23
B_7	12.56	12.60	−40	−0.31
B_8	12.59	12.63	−40	−0.31
B_9	12.60	12.63	−30	−0.23
B_{10}	12.59	12.62	−30	−0.23
B_{11}	12.57	12.61	−40	−0.31
B_{12}	12.51	12.55	−40	−0.31

Table 4
Voltage deviations (in mV) from 20 °C measurements at different ambient temperatures

Battery	−20 °C	−10 °C	0 °C	10 °C	30 °C	40 °C
B_1	0	0	0	0	0	0
B_2	−10	−10	0	−10	0	0
B_3	−20	−10	−10	0	+10	+10
B_4	−30	−20	−20	−10	0	0
B_5	−20	−20	−10	0	+10	0
B_6	−30	−10	−10	−10	+10	+20
B_7	−20	−10	−10	−10	+10	+10
B_8	−20	−20	−10	−10	−10	0
B_9	−20	−20	−10	−20	−10	−10
B_{10}	−10	−10	−10	0	0	0
B_{11}	−10	−10	0	+10	0	0
B_{12}	−30	−20	−10	−10	0	0

memory. These correction factors will have to be updated at specific intervals of time to account for the changing electrochemical properties of the batteries over time. A procedure to this effect is currently under development.

The circuit performance was examined over a temperature range of −20 to 40 °C [20]. During each temperature test, the circuit was allowed to "soak" for atleast 4 h 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 deviations (in mV) from the 20 °C measurements for the −20 to 40 °C temperature range. It can be observed 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. 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 20 to −20 °C temperature range. The deviation in the B_4, B_6, and B_{12} voltage measurement is shown in Fig. 9 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,

$$\Delta V_4 = V_{\mathrm{B}_4\text{-}T} - V_{\mathrm{B}_4\text{-}20} \tag{5}$$

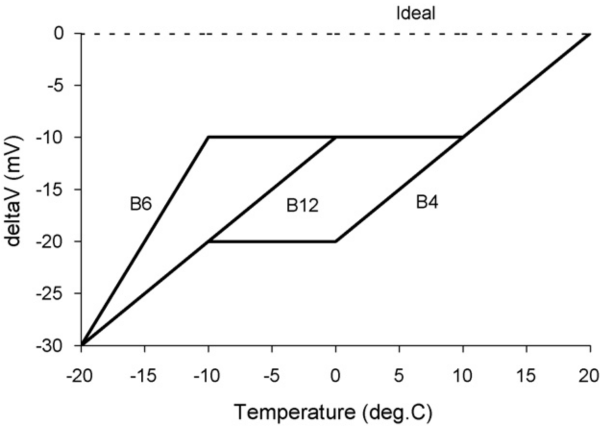


Fig. 9. B_4, B_6, and B_{12} results for the −20 to 20 °C range.

where $V_{\mathrm{B}_4\text{-}T} = V_{\mathrm{B}_4}$ at the specified temperature and $V_{\mathrm{B}_4\text{-}20} = V_{\mathrm{B}_4}$ at 20 °C.

It can be observed from Fig. 9 that as the ambient temperature decreases, the monitor measurements tend to decrease. This probably is a result of the temperature effect on the relay contact resistance, which tends to increase with a decrease in ambient temperature.

4. Conclusions

High performance batteries for applications such as electric vehicles and uninterruptible power supplies will require precise monitoring of the individual voltages in the series connected battery pack. Since previous monitoring schemes have proven inadequate and/or uneconomical, a new electromechanical-based voltage measurement circuit was developed to transfer each voltage to a common reference. The approach proved to be very effective and precise for measuring 12 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. The circuit can also easily be modified for measuring voltages from packs having more than 12 batteries. This would, however, require a larger voltage scan time. Initial tests have showed that packs with 48 series connected batteries only required a scan time of a few seconds. This indicates that the system might be impractical for high performance applications involving packs that possess more than 48 batteries.

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 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 3×10^5 switching operations at a relatively high power rating of 2 $\mathrm{A_{dc}}$, 30 $\mathrm{V_{dc}}$ [14,15]. This indicates that the circuit should have a fairly long life.

Several tests were carried out in order to evaluate the voltage measurement circuit over a wide temperature range. 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.

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