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Short Communication

Voltage Reversal in Series-connected Three 1.5V AAA Alkaline Batteries

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Discharge curves for three 1.5V AAA alkaline batteries, series-connected, were completed. The voltage across each battery as a function of time has been directly measured. For this purpose a specific measuring system has been built. Periodically, by means of a switches block, consisting of reed relays pairs, terminals of each battery are successively connected to the floating inputs of an analog-to-digital converter. The whole measurement process runs continuously, automatically, without human or computer assistance. By using the described system, batteries unbalance and reversal voltage effect occurring in over-discharge conditions have been noticed.

Keywords: alkaline battery, electrochemical battery, batteries unbalance, voltage reversal, forced discharge

1. INTRODUCTION

Electrochemical batteries represent the most widespread energy source for the electronic portable devices, as well for electric vehicles. Consequently, the studies regarding development of new types of batteries or improvement of those which already exist are of great interest. For most applications, in order to obtain the necessary operating voltage, batteries consist of several cells connected in series. Even if the cells are manufactured under the same conditions, by using the same technology, their characteristics are not identical. As a result, series-connected cells voltage may differ from one another. These differences, which can be initially very low and undetectable, increase significantly during the battery discharge or after several charge and discharge cycles. This behavior is called the cell unbalance. In some circumstances, one or more of cells voltage can reach 0V, eventually changing their polarity. This effect, called the voltage reversal or the forced discharge, is potentially dangerous and it should be avoided as much as possible [1, 2]. The performances of an unbalanced cells series string, assembled either as a single battery or as multiple batteries, worsen considerably. A few approaches to correct or diminish the effects of the cell unbalance have been proposed and are currently employed [3]-[7]. However the existing solutions are not perfect, for their implementation additional external circuits are needed and hence, the complexity and cost of the applications increase. Their effectiveness must be checked during battery run time. Therefore further studies, including the refinement of the measurement methods, are necessary [8]. Within this general goal, the aim of the present study was to implement an accurate method allowing the direct observation of the voltage variation and a possible voltage polarity change, across of the series-connected cells, during the discharge process.

The operation of the measuring system is similar to that of a multichannel data logger. At present, various sorts of multichannel data loggers are currently produced and commercially available. However for most of them, the ground terminal is common for all channels, therefore the voltage across series-connected cells terminals cannot be directly measured, but only calculated. For example, in the case of a string of three cells series-connected, as it is shown in Fig. 1, if common ground is connected to the terminal T_1, only U_1 would be directly measured, as the voltage between the terminals T_2 and T_1. Voltage U_2 must be calculated by measuring the voltage between the terminals T_3 and T_1, then subtracting U_1, whereas U_3 must be calculated by measuring the voltage between the terminals T_4 and T_1, then subtracting the sum U_2+U_1. For longer cells string, more iterations are needed, leading to errors accumulation. Measurement procedure detailed above implies that, either the maximum permissible voltage at data logger inputs is at least equal to the sum of the maximum voltages delivered by each of cells series-connected (*i.e.* $U_1+U_2+U_3$) or a voltage divider is used. In both cases, the measured voltage across each cell is less accurate. In our approach, the inputs of a voltage measuring device are successively connected to the terminals of each cell of the string. This measurements cycle are repeated at regular intervals, results are stored in a non-volatile memory, being then transferred to a PC. Because both inputs are floating, voltages across any terminals are directly measured. Maximum permissible input voltage for the measuring device must be at least equal to the maximum voltage delivered by a single cell.

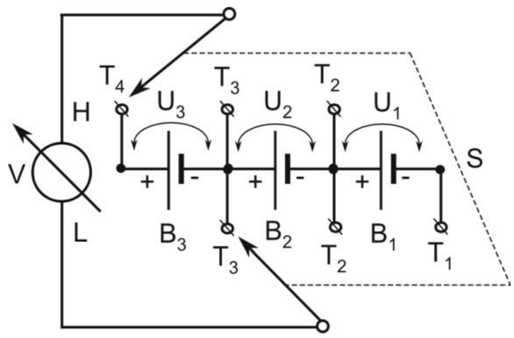

Figure 1. Equivalent electrical circuit of the measuring system. Components: V-voltage measuring device with floating inputs, denoted H and L, respectively; S-three poles dual switch; B_1, B_2, B_3-cells under test. By means of the switch S, the inputs of the voltage measuring device are successively connected to the cells terminals T_2-T_1, T_3-T_2 and T_4-T_3, measuring voltages U_1, U_2 and U_3 across them.

2. EXPERIMENTAL

2.1 Measuring system

The block diagram of the measuring system, which operates according to the procedure outlined above, is shown in Fig. 2. The analog-to-digital converter (ADC) has integrated auto zero and auto polarity circuits, being characterized by a very low input current (typical 1pA), floating inputs (H and L) and a good voltage resolution for the considered application (±1mV). It can measure both positive and negative voltages, without any external interface circuits, in the range from -1.999V to +1.999V. A resistor R_i=1MΩ is connected between analog inputs in order to prevent noise pick-up and electrostatic over stress. The real-time clock circuit (RTC), keeps the track of the current time and provides time stamp for each voltage measurement. A non-volatile memory (NVM) has the role to store, locally, measurements result. The switches block (SB) has the role to connect, one at a time, one cell to the floating inputs of the ADC, denoted H and L. This acts as a three poles dual switch (S in Fig. 1). Therefore, the inputs of the voltage measuring device are successively connected to the cells terminals T_2-T_1, T_3-T_2 and T_4-T_3, measuring voltages U_1, U_2 and U_3 across them.

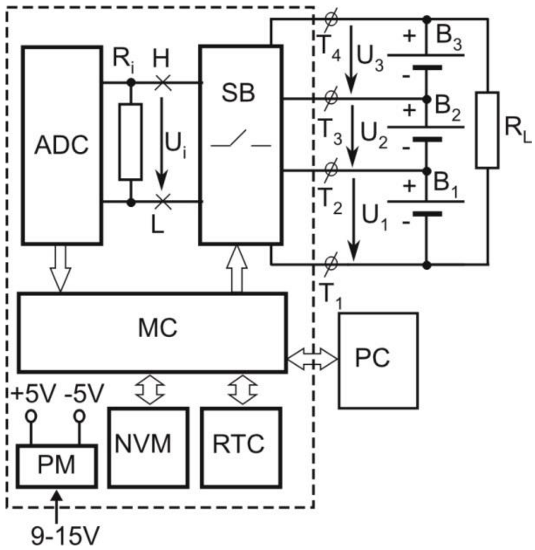

Figure 2. Block diagram of the measuring system (within the dotted box) and external elements. System components: analog-to-digital converter (ADC); real-time clock (RTC); non-volatile memory (NVM); switches block (SB); microcontroller (MC); power module (PM). External element: personal computer (PC) which communicates with the measuring system through one of its serial ports. The B_1, B_2, B_3 are series-connected cells under test, and the R_L is the load.

The microcontroller (MC) runs the measurement and the acquiring operations, independently of any external command. Also, it assures communication with PC by means of the serial port. All necessary voltages for the measuring system elements are provided by the power module (PM). The personal computer (PC) operates as an external element attached temporarily to the measuring system. A software application with graphical user interface, running on a PC, specifically developed for this purpose, allows to change settings, download the data stored by the NVM, start or stop a new measurements set. The downloaded binary data are decoded and saved in files stored on the PC hard disk, in the form of a human readable text. A photograph of the measuring system is shown in Fig. 3.

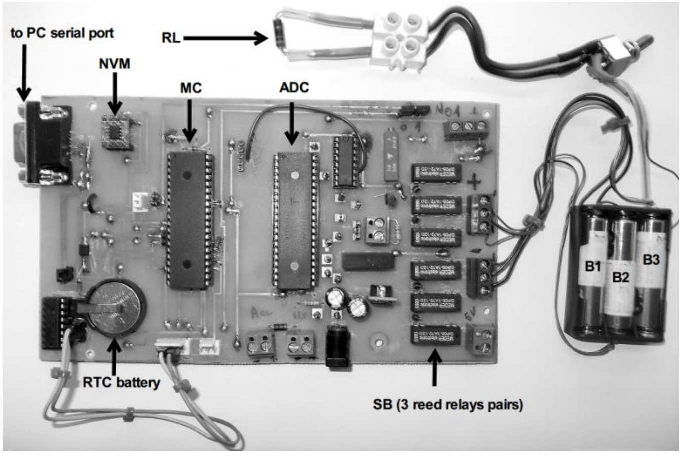

Figure 3. Top side of the measuring system electronic circuit board

2.2 Measurement process

The voltages across the cells terminals, U_1, U_2 and U_3, are not measured simultaneously but successively, one by one. For this purpose, by means of the SB, the two terminals of each cell (*i. e.* anode and cathode) are routed to the corresponding ADC inputs, meaning that anode and cathode are connected to the H and L inputs, respectively. Switches block (SB), whose topology is shown in Fig. 4, consists of a network of six reed relays, grouped into three pairs: Ry1L-Ry1H, Ry2L-Ry2H, Ry3L-Ry3H. Each pair acts as a dual switch.

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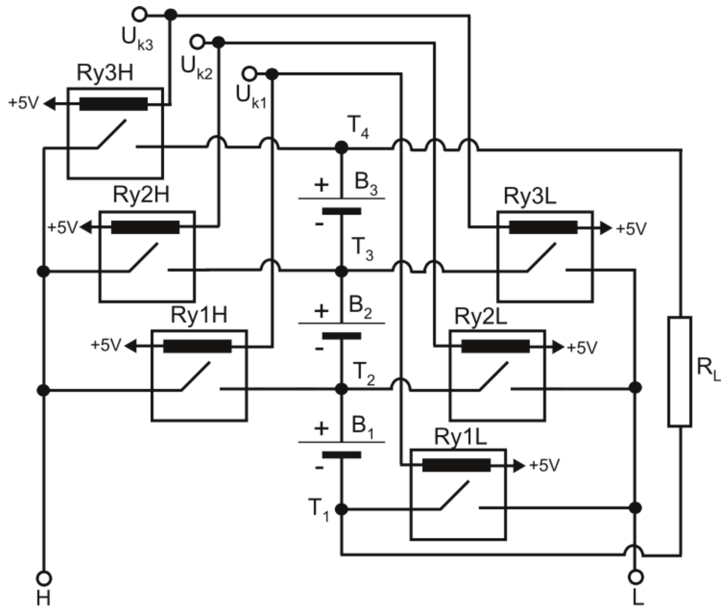

Figure 4. Switches block (SB) topology

As a function of the voltage U_{kx} (x=1, 2, 3), the contacts of each pair of reed relays can be, simultaneously, either closed (if U_{kx}=0V) or open (if U_{kx}=5V). Voltages U_{kx} are controlled by the MC so that, at a certain moment, either a single dual switch is on or all dual switches are off. Before and after each voltage measurement both ADC inputs are disconnected. The succession of the operations for a complete measurement cycle is shown in Table 1. During a complete measurement cycle, voltage across each cell is measured once.

Table I. Steps succession for a complete measurement cycle

Step	Mode (abbreviation)	Input H connected to:	Input L connected to:	Relays state
1	No measurement	Not connected	Not connected	Ry1H,L off; Ry2H,L off; Ry3H,L off
2	U_1 measurement	T_2	T_1	**Ry1H,L on;** Ry2H,L off; Ry3H,L off
3	No measurement	Not connected	Not connected	Ry1H,L off; Ry2H,L off; Ry3H,L off
4	U_2 measurement	T_3	T_2	Ry1H,L off; **Ry2H,L on;** Ry3H,L off
5	No measurement	Not connected	Not connected	Ry1H,L off; Ry2H,L off; Ry3H,L off
6	U_3 measurement	T_4	T_3	Ry1H,L off; Ry2H,L off; **Ry3H,L on** Back to step 1

3. RESULTS AND DISCUSSION

Time variation of the voltage across the terminals of three identical cells series-connected has been recorded by using above described measuring system. Each cell consisted of a commercial available not rechargeable 1.5V AAA alkaline battery. All batteries were from the same pack and it can be assumed that they were produced at the same time, following the same technology and were stored in similar conditions. For about 5492 minutes (≈91.5 hours) the three series-connected batteries has been connected permanently to a load R_L=75Ω. After that, the load was disconnected. The time variation of voltages measured across the three batteries, U_1, U_2 and U_3, both with and without load are shown in Fig. 5. The interval between two successive voltage measurements for the same battery was T_C=359±1s. The batteries unbalance and battery B_1 voltage reversal are very clearly exposed. After the load is disconnected, it can be seen that, the batteries voltage asymptotically goes up to a common value. It can be noticed that the voltage U_1, initially reversed after discharge process, returns to its normal polarity.

The SB is equipped with reed relays because of several reasons. A reed relay is a type of electromechanical switch. During on state, voltage drop across electrical contacts of an electromechanical switch is practically zero, whereas during off state the leakage current is negligible. These features are very important in the case when precise measurements of low voltages are required. An electromechanical switch operates identically, regardless of the current direction through its contacts. As it can be seen in Fig. 5, even in a simple and pure dc circuit, in some conditions, voltages polarity across various elements can be reversed during time in an unpredictable manner. Finally, the electromechanical switch contacts are genuine floating because they form a passive circuit element which does not need to be electrically supplied. For the described application, there are no real alternatives based on solid state devices that meet all these attributes. Examples of similar solutions for various measurement setups are reported in recent literature [9]-[11]. Despite the advantages mentioned before, an important drawback of this approach must be admitted, namely the finite lifetime of the electromechanical switches, in terms of on/off operations number, issue which eventually could falsify measurements results. However, in the case of the reed relays, the life expectancy, at low current and for resistive load, is large enough for application described here, its order of magnitude being better than 10^7 operations. Ultimately, to address such concerns, the reed relays can be regarded as consumables and replaced periodically.

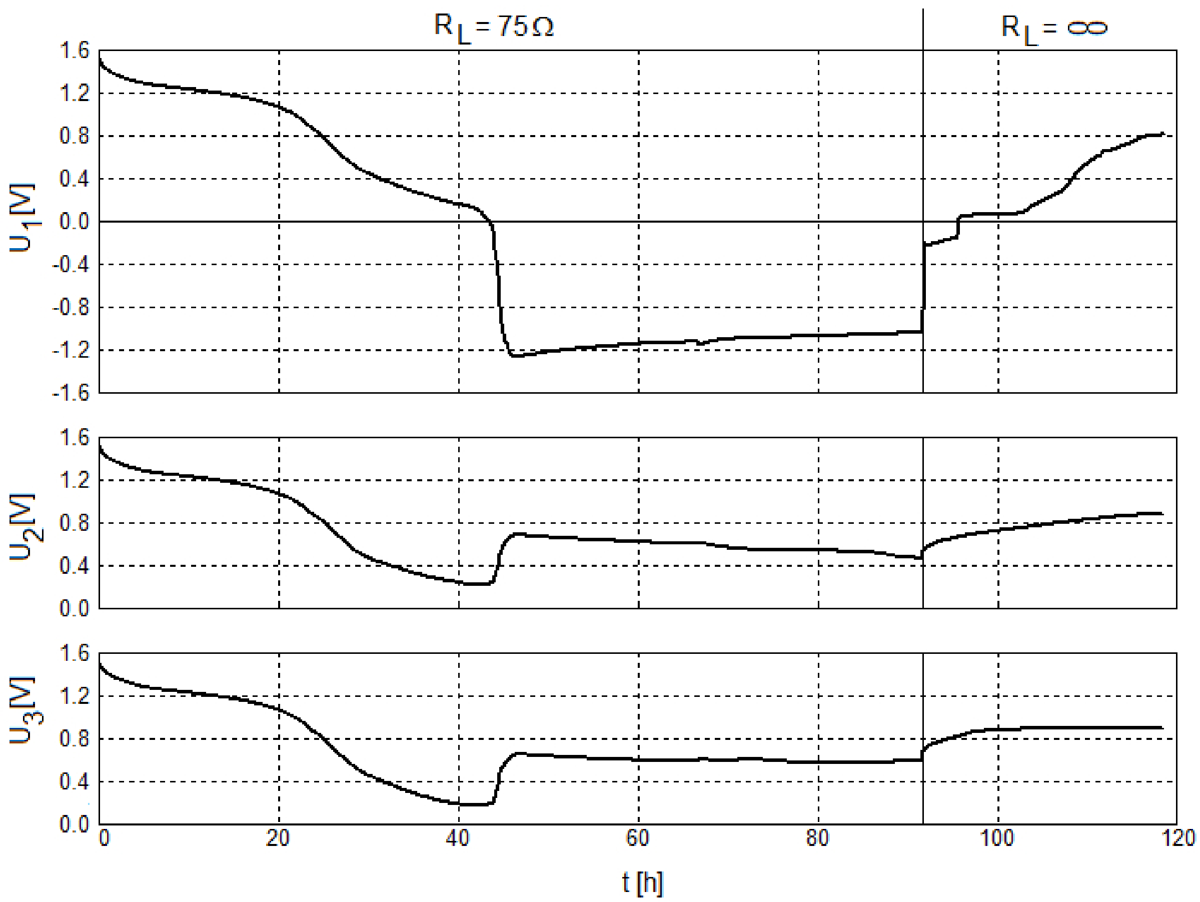

Figure 5. Time variation of the voltages measured across the three batteries, U_1, U_2 and U_3, with (R_L=75Ω) and without (R_L=∞) load. Time is given in hours. The U_2 and U_3 keep their initial polarity, whereas U_1 changes twice its polarity. The thin vertical bar marks the load removal. Interval between two successive voltage measurements for the same battery T_C=359±1s.

Discharge curves, showing and tracking voltage reversal of the series-connected cells are rarely reported in literature. Most of this kind of studies ended when the cell voltage drops under cutoff voltage. Due to the specific automotive applications, voltage discharge processes have been especially investigated, both theoretically and experimentally, for the case of the lead-acid cells (*e.g.* [2], [12], [13]). We proposed a measuring method making possible the monitoring of the voltage variation across each of series-connected cell, including polarity change. The unbalance and reversal voltage effect, for the series-connected batteries, during discharge process has been directly observed. Results demonstrated their presence, inclusively, in the case of the alkaline batteries. Appearance of the discharge curve, in the case of the voltage reversal occurrence, is similar to that found for a Plantè cell discharge, reported in [2].

4. CONCLUSIONS

Based on the principle described here, various new implementations are possible. By adding reed relays pairs, the number of cells series-connected can be increased. Also, a supplementary reed relay, controlled by MC, could be inserted into the load circuit, allowing to study the intermittent discharge of the series-connected cells strings, according to a given scheme.

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