ANALYSIS OF THE STATE OF CHARGE OF RECHARGEABLE DC SOURCES TO OPTIMIZE THEIR EMBEDDED CONTROL SYSTEMS

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In this paper the behavior of rechargeable DC sources is approached in different states of charge (SoC), using PSPICE simulation program. The simulation was performed for both the assembly in series and in parallel comprising batteries based on Li-ion cells. The results demonstrated that different states of charge of the cells that are forming the battery influence considerably the output current intensity which can be produced, reducing the battery lifespan and causing replacement sooner than expected. Thus, optimizing the control systems of the battery, including monitoring and related adjustment of functioning of the cells gives the possibility to enhance its lifetime and intensity of use.

Key words: rechargeable batteries, modeling, cells imbalance, SoC, control system

1. **Introduction**

Different economic sectors have significant needs related to the use of rechargeable batteries. For example, household electronics (mobile phones, laptops, PDAs, etc.) uses relatively small batteries with high energy density and low power. Other sectors such as an electric car industry are using renewable high capacity rechargeable batteries with high voltages and high currents. Because the cells, including Li-ion types, have the voltage at the terminals of the order of volts, the batteries are obtained by connecting cells in series (for high voltage), parallel (for the current intensity) or mixed [1].

When using the rechargeable electrochemical cells to obtain multiple cell batteries, different aspects must be taken into account as is, for example, safety of use. Thus, when a Li-ion battery is charged to a voltage exceeding 4.2 V, it can be damaged due to thermal effects occurring and may even lead to fire [2] and therefore it is strongly recommended using overvoltage protection systems.

A second aspect is the need to consider the life span of the cell and therefore that of the battery. When exceeding values of electrical quantities specific to the charging procedure, some accelerated electrochemical phenomena degradation occurs within the cell and also the reducing of the duration of use [3].

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For example, increasing the charge voltage of 4.2 V to 4.25 V, the degradation of the cell is 30%.

A third consideration is the possibility of using cells that are only partially loaded. If a battery electronic protection acted, at least one of the cells will be charged only partially and the voltage at the terminals Li-ion battery will be lower than 4.2 V multiplied by the number of cells connected in series [4].

One aspect that could lead to battery damage is the limited use of energy from the battery cells. When one of the cells reaches the imposed discharge limit (2.7 V for the LiCoO2 cell), the protection system switches off the discharge, even if all the other cells are not discharged up to the required level [5]… [10].

It can be observed that the emergence of differences in voltage values between the battery cells may cause problems such as different electromotive force voltages (EFV) of the cells in open circuit functioning and also different values of the internal resistance of the cell components in the battery load operation [5] ... [7].

The differences between the state of charge (SoC) of the cells represent the cause of the differences in voltage between them in open circuit (OCV - open circuit voltage).

The relationship $OCV = f(SoC, T)$ shows an expression that depends on the electrochemical process and temperature but it is evident that to a change in the state of charge receive a difference in the open circuit voltage. For example, if between two Li-ion battery cells is a voltage difference of 1%, then between their states of charge will generate a difference of about 10 mV at the end of charge and of 100 mV ÷ 500 mV at the end of the discharge [8], [9].

In this paper are analyzed, by modeling and simulation, the phenomena that may lead to damage multiple cells rechargeable batteries.

2. Modelling batteries with different charge states of the cells

2.1. Modeling the unbalanced battery with cells with different states of charge

Modeling of circuits for Li-ion battery refers, initially, to cells connected in parallel, in order to achieve high currents. Using PSPICE software package, various structures are analyzed starting from batteries with cells in the same SoC to the batteries with maximum imbalance between cells SoC. The cases studied here are:

a) 4 cells with identical electromotive force voltage and internal resistance, 100% SoC;
b) 3 cells with 100% SoC and 1 cell with 50% SoC;
c) 3 cells with 100% SoC and 1 cell with 15% SoC.

The values of electromotive force voltage and of internal resistance of Li-ion cells to different SoCs are specified by the manufacturer - Table 1.

External circuit resistances are about 1 Ω and, respectively 10Ω.

Table 1

Electrical parameters of cells

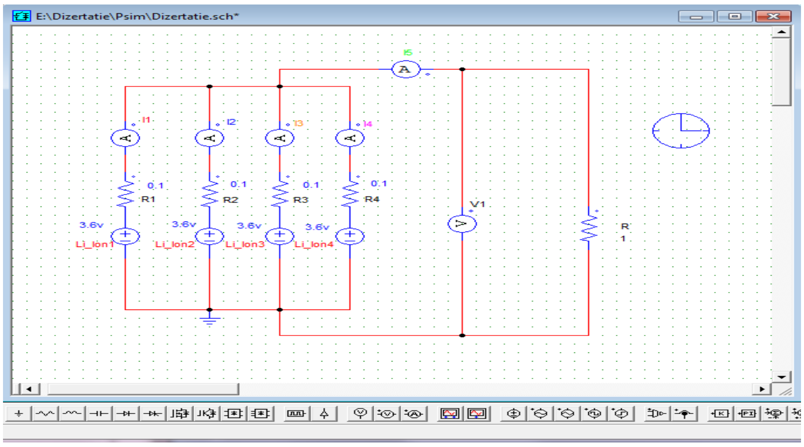
Battery type	Cell EFV (V)	Internal resistance (Ω) at 20°C			External resistance (Ω)
		SOC 100%	SOC 50%	SOC 15%	
Li-ion	3,6	0,1			1

	3,2		0,25		10

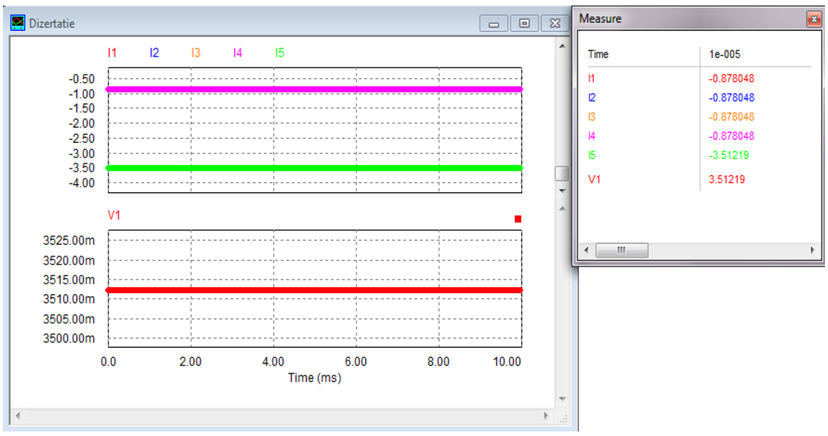
a. *Battery with four 100% SoC cells mounted in parallel*

a1) External resistance R = 1 Ω - Fig. 1

Currents debited from each of the four cells are identical I1 = I2 = I3 = I4 = 0.878 A and the current I5 through external resistor are their sum. The battery voltage Ub = 3.512 V is less than EFV in normal SoC (3.6 V) due to the voltage drops across the internal resistance. In the external circuit is used only 88.3% of the total electrical energy produced by the electrochemical conversion in these four cells, the difference being losses by joule effect within the battery.



a) Circuit scheme

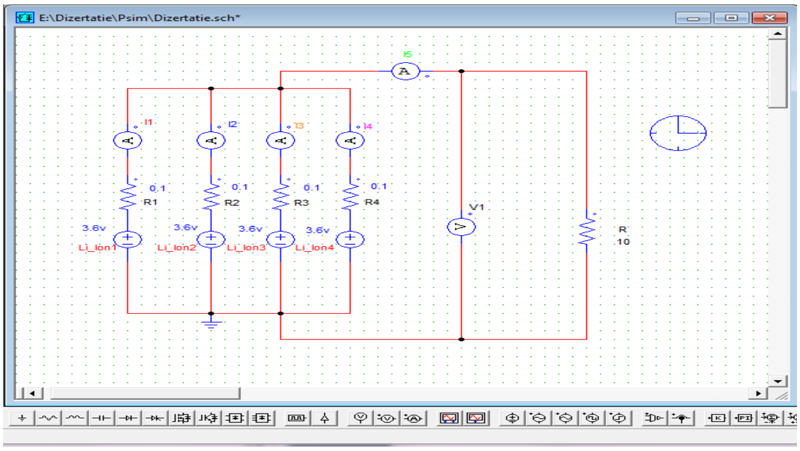


b) Simulation results

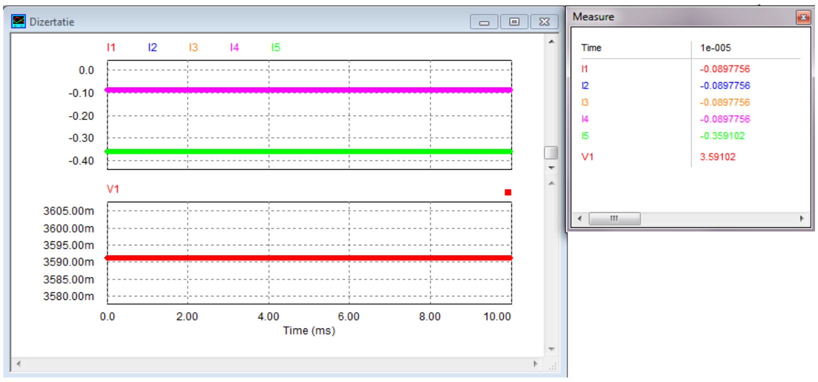
Fig. 1 Battery with 4 cells SoC=100%, external resistance R=1 Ω

a2) External resistance R = 10 Ω - Fig. 2

It can be observed the similarity of currents intensity through the cells, but their value is smaller than the previous one I1=I2=I3=I4=0.0897A, the voltages drop across the external resistances decreased so that 99% of the energy produced by the electrochemical conversion battery cells may be obtained in the external circuit. Terminal voltage Ub=3.591 V is closer than the one from open voltage circuit.



a) Circuit scheme



b) Simulation results

Fig. 2 Battery with 4 cells SoC 100%, external resistance R=10 Ω

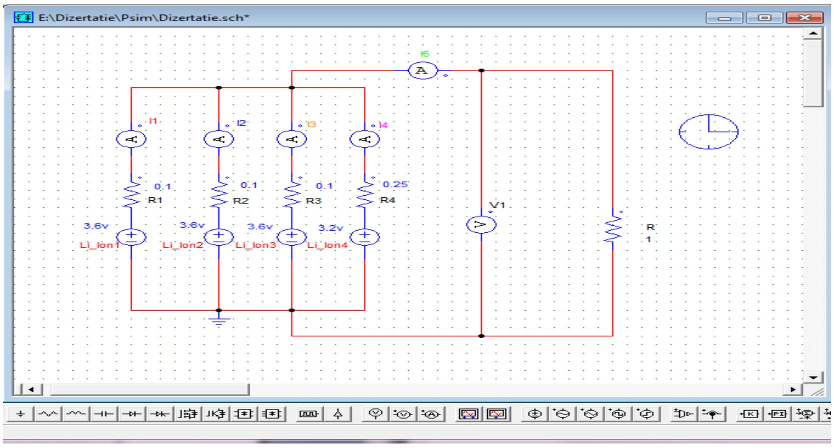
Modeling these circuits make it clear that in the case of a battery built from cells with identical SoC does not appear any imbalance of the state of charge of the cells during operation.

b. *Battery with 3 cells SoC 100% and one cell SoC 50%*

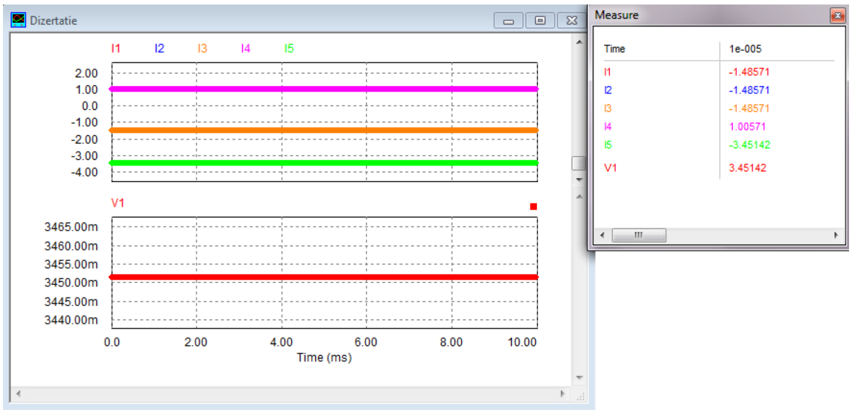
b1) External resistance R = 1 Ω - Fig. 3

The currents through the three identical cells are similar I1 = I2 = I3 = 1.485 A and through the fourth cell, which has a state of charge SoC of 50%, the current is reversed, meaning that this cell is loaded at the expense of the stored energy in the other three cells.

The available external energy is only 86% of that produced by the electrochemical conversion in the full charged cells, less than in the case of a1) of the identical cells. The voltage at the battery terminals, Ub = 3.451V, is smaller than in the undifferentiated cells case with nearly 2%.



a) Circuit scheme



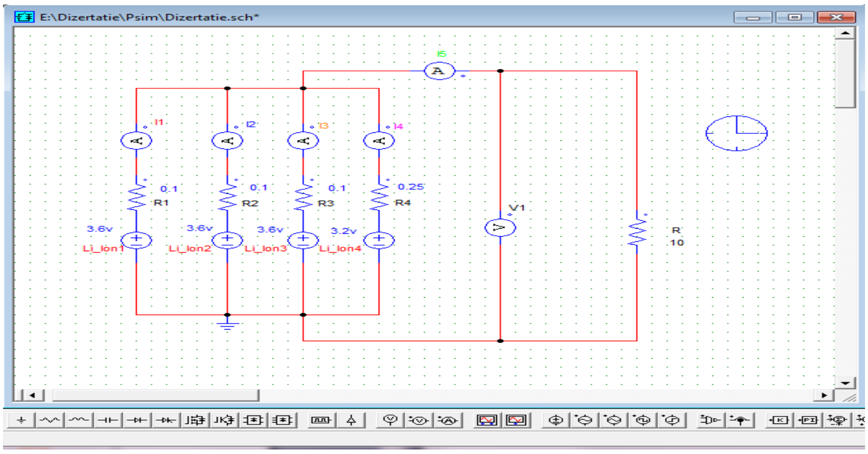
b) Simulation results

Fig. 3 Battery with 3 cells SoC 100% and a cell SoC=50%, external resistance R=1 Ω

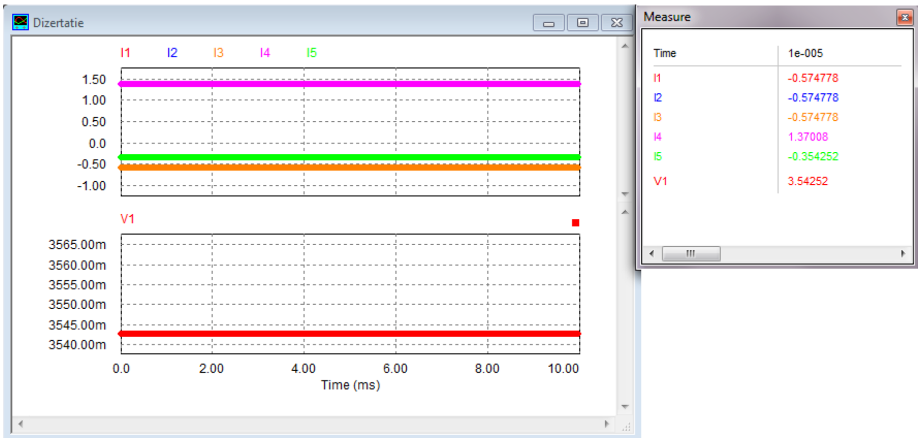
b2) External resistance R = 10 Ω - Fig. 4

The currents through the three identical cells are identical I1 = I2 = I3 = 0.574 A and through the fourth cell, which has a state of charge SoC of 50%, the current is reversed, meaning that this cell is loaded at the expense of the stored energy in the other three cells.

The intensity of I5 current has a value of almost 3 times bigger than the one produced by normal cells. From the energy produced in the full charged cells only 22% reach in the external circuit, the rest contributing to the loading of the unbalanced cell.



a) Circuit scheme



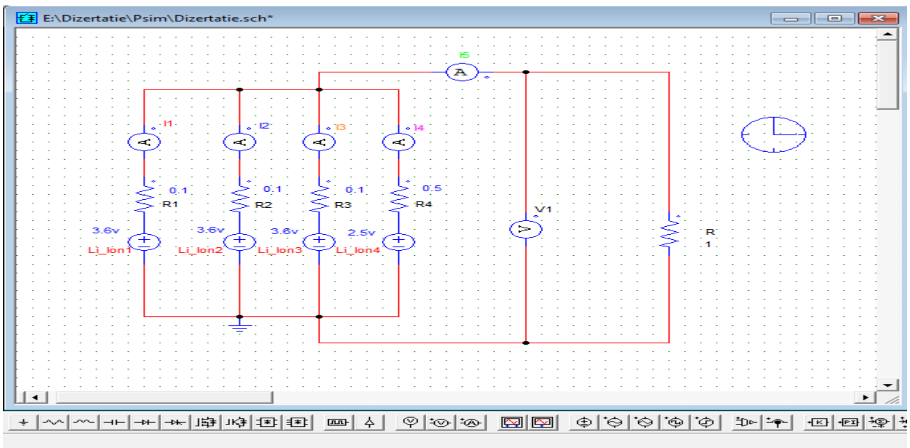
b) Experimental results

Fig. 4 Battery with 3 cells SoC 100% and a cell SoC = 50%, external resistance R=10 Ω

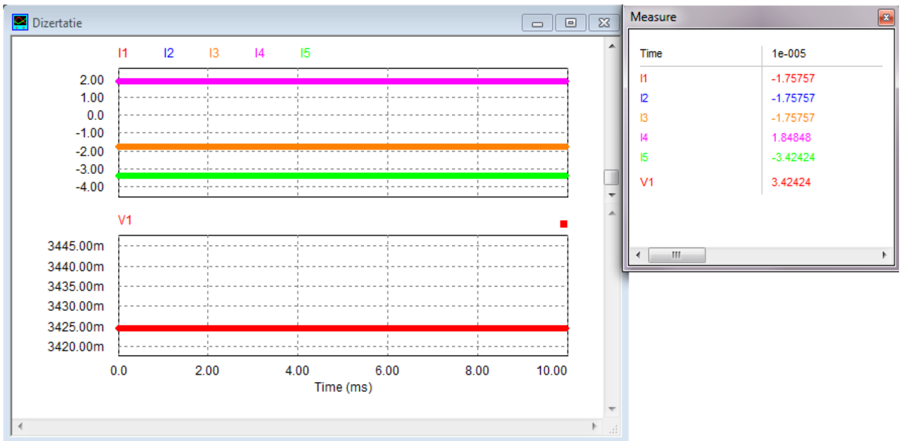
c. *Battery with 3 cells SoC 100% and 1 cell SoC = 15%*

This is the case in which one of the four cells is almost fully discharged.

c1) External resistance R = 1 Ω - Fig. 5



a) Circuit scheme



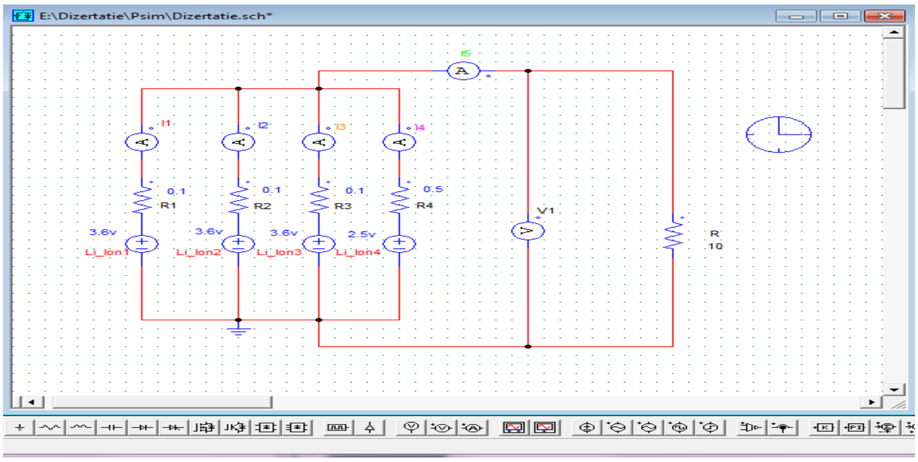
b) Simulation results

Fig. 5 Battery with 3 cells SoC 100% and a cell SoC = 15%, external resistance R=1 Ω

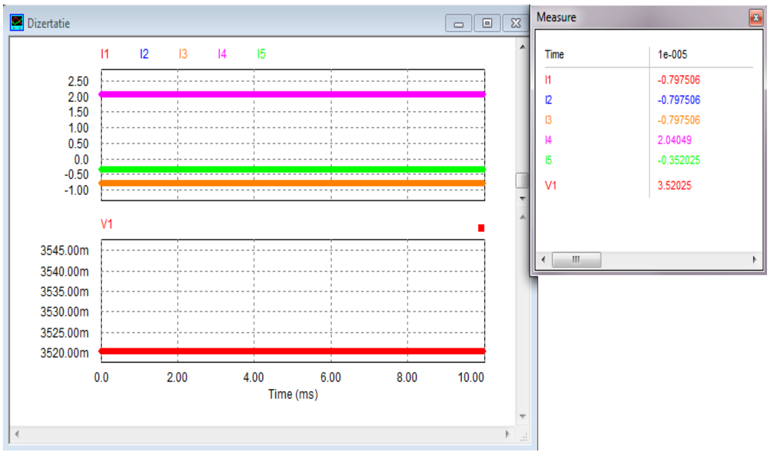
Compared to the previous circuit, in this case in which the fourth cell has 15% SoC, the charging current is increased even more at the expense of the energy of the other three cells. A percentage of only 59% of the energy produced by the electrochemical effect in the three cells 100% SoC is used by the external circuit, the energy used to balance the cell with SoC 15% being the biggest of the studied cases. It worth to mention the fact that the thermal regime of the system is depreciates due to Joule effect which increases the temperature of the battery.

c2) External resistance R = 10 Ω - Fig. 6

In this case, in which the flowing out current is reduced, the imbalance leads to an increase of the currents produced by the three cells SoC 100% and of the charging current of the fourth cell, almost empty.



a) Circuit scheme



b) Simulation results

Fig. 6 Battery with 3 cells SoC 100% and 1 cell SoC = 15%, external resistance R=10 Ω

It is immediately apparent that only the terminal voltage indicator is not sufficient to indicate imbalances inside the battery while we do not have information on significant currents that could lead to undesirable thermal effects. From the results obtained from modeling these situations that may occur in the operation of batteries, results a few conclusions:
- The intensity of the output current drops out when there are imbalances between cells SoC;
- The current through the battery cells can have different directions in the SoC imbalance situation, some cells being loaded at the expense of energy stored in those cells with 100% state of charge SoC;
- The energy available in the external circuit can become extremely small in the case of a strong imbalance between the battery cells;
- Terminal voltage can obtain small values in the case of imbalance between cells, indicating a possible renunciation of that battery;
- The observed phenomena are attenuates when external circuit resistance increases, contributing to currents lowering.

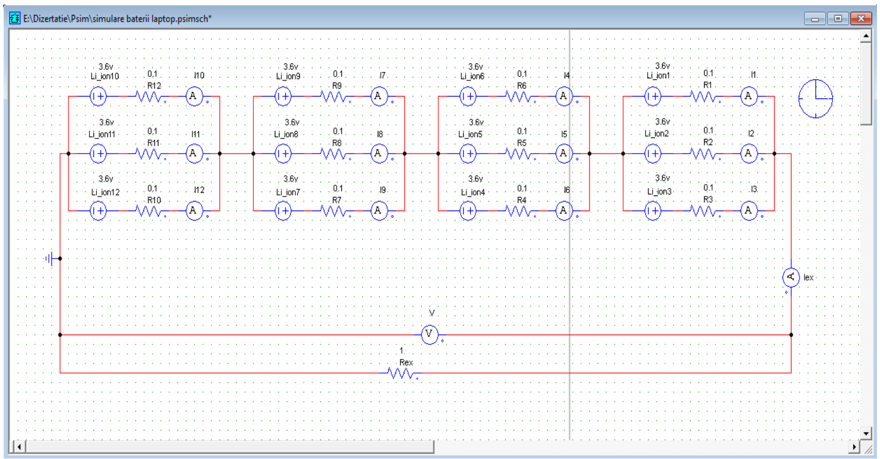
2.2. Modeling of Li-ion batteries for IT equipment

The battery structure is the following: four groups of cells in series, each group being composed of three cells connected in parallel. The cases studied are:

a. *All cells with 100% SoC.*

a1) External resistance R=1Ω

In Fig. 7 we can observe the fact that the current intensity through each cell is the same (4.235 A), and the current in the external circuit is Iout = 12.7 A. Terminal voltage is set Ub = 12.7 V.



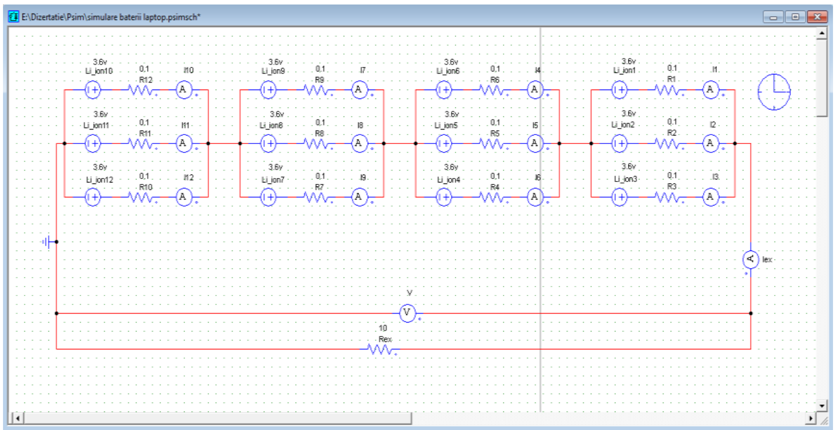
a) Circuit scheme

b) Simulation results

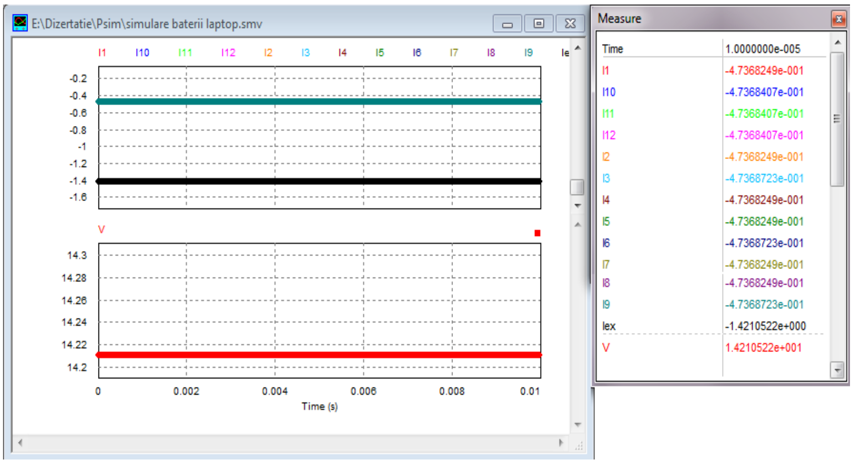
Fig. 7 Four batteries with all cells SoC=100%, external resistor R=1Ω

a2) External resistance R=10Ω - Fig. 8

In this case, there is a decrease of the current through all the cells (0.473 A) and through the external circuit. Terminal voltage increases to the value of U_b = 14.21 V.



a) Circuit scheme



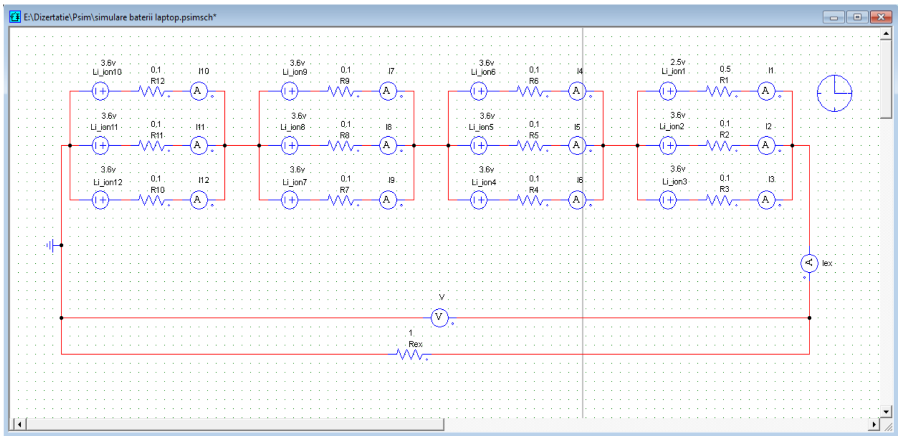
b) Simulation results

Fig. 8 Four batteries with all cells SoC=100%, external resistor R=10 Ω

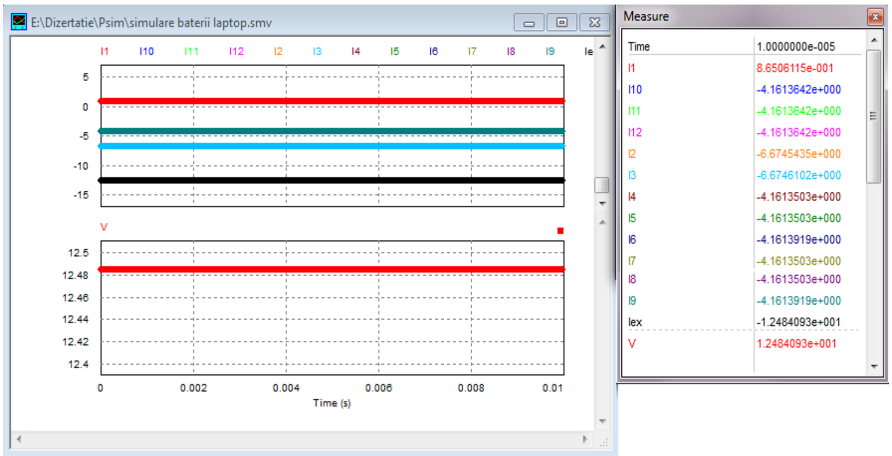
b. *Battery with a discharged cell at 15% SoC and all the others cells at 100% SoC*

b1) External resistance R=1Ω

The cell with the level of charge of 15% is charged with a current of 0.86 A by the other sources, the current in the external circuit drops to 12.48 A and the value of the terminal voltage drop up to Ub = 12.48V. In the external circuit reach 64% of the energy produced by the rest of 11 cells and the rest of energy balances the twelfth cell and cover the internal cell voltage drops.



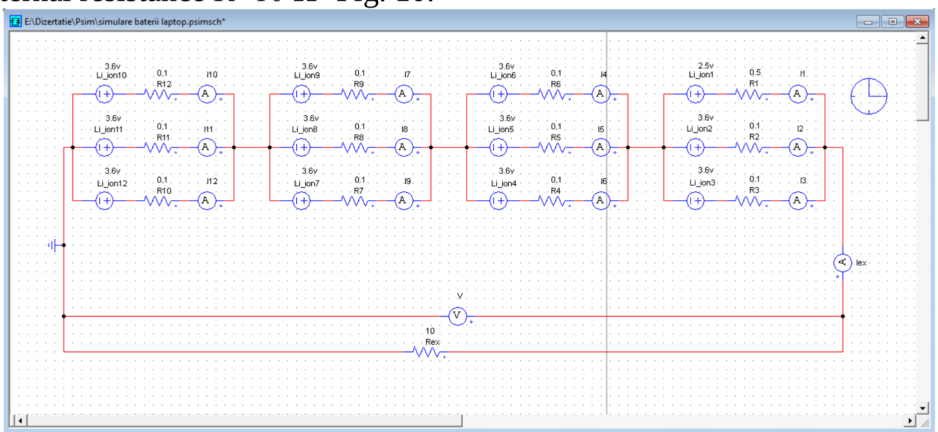
a) Circuit scheme



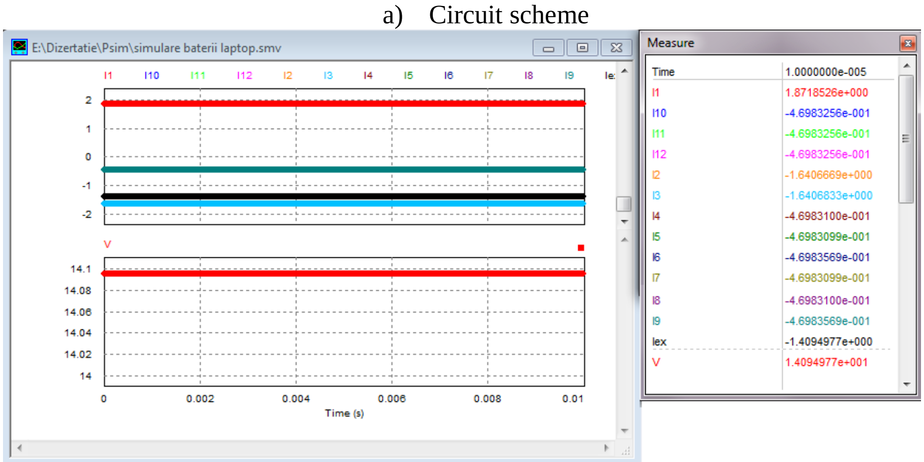
b) Simulation results

Fig. 9 Battery with a discharged cell at 15% SoC and all the other cells at 100% SoC, external resistance R=1Ω

b2) External resistance R=10 Ω -Fig. 10.



a) Circuit scheme



b) Simulation results

Fig. 10 Battery with a discharged cell at 15% SOC and all the others cells at 100% SOC, external resistance R=10 Ω

It can be observed the change of current direction through the discharged cell.

The study was conducted on a simple structure of the battery with few cell and a Li-ion battery for use IT equipments.

The imbalance between different state of charge (SoC) of the cells can lead to real change of parameters and the battery overheating. The modeling results show that cells with various discharge levels lead to high imbalance amog cells and to the way the energy produced by electrochemical effect is transferred for charging the strong imbalanced cells. In order to protect the battery, it is necessary to eliminate imbalances of rechargeable battery cells, through the use of control systems, designed in accordance with the capacity and construction of the battery

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