Charge Equalization Unit for a NiCd Battery of Small Earth Observation Satellite EPS Simulation

M. ZAHRAN

Electronics Research Institute, NRC Blg., El-Tahrir St., Dokki, 12311-Giza, EGYPT &
Member in Space Program of National Authority for Remote Sensing and Space Science,
23 Josef Tito St., Nozha, Cairo Egypt. Tel/Fax. +202-6225821/6225833.

Abstract: - In micro, mini and small satellites because of needs for higher bus voltage and small required battery capacities, batteries are nearly always used in series combinations of multiple cells. When a series string of cells is charged as a group, a single current is imposed on all the cells. However, if the voltages begin to differ, the result is a charge imbalance that can lead ultimately to battery failure. In any useful series battery charge process, some type of “charge balancing” or “equalization” must take place to restore balance or at least prevent it from growing. This paper reviews battery behavior and performance related to the equalization problem, in the context of Nickel Cadmium batteries. Equalization processes can extend the life of battery packs. Active equalization with a DC-DC converter speeds the process and supports exchange (sharing) with the weak cell(s) Passive equalization is too slow in most contexts for strings longer than about 12 cells especially in a space applications. *A Matlab Simulink model is built for a charge equalization unit of a 22 cells NiCd battery stack. Model is tested with a resistive load as well as with real battery cells. Simulation results confirm the applicability of the equalization control technique.*

Key Words: - NiCd Battery equalization, battery management, charge/discharge Control, Charge Equalization Unit (CEU), Low Earth Orbit (LEO), Earth Observation Satellite (EOS), Electric Power System (EPS)

1. Introduction

Nickel Cadmium (NiCd) and Nickel Hydrogen (NiH2) batteries are the most common types of batteries for low altitude space missions. They have similar characteristics. NiCd batteries are not very energy-dense, but they are inexpensive, lightweight, and extensively proven for LEO space application.

Battery is composed of one or more cells, either parallel or series connected to obtain a required current/voltage capability (batteries comprised of series connected cells are by far the most common). Proper electric and thermal management of battery pack, consisting of many series cells, is imperative.

During operation, voltage and temperature differences in the cells can lead to electrical imbalances from cell to cell and decrease pack performance by as much as 25%. An active battery management system (BMS) is a must to monitor, control, and balance the series cells pack [5]. The need for equalization is well established. An equalization process is intended to match the SOC among cells in a string. Charge equalization is an important part of the charge/discharge process for series-connected battery cells. Active equalization provides clear life advantages over other approaches. The results are consistent with the hypothesis that a properly designed active equalization process can provide battery cycle life for a series string that matches the cycle operating results for an individual cell [1].

2. Problem Definition

In multi-cell batteries, because of the larger number of cells used, we can expect that they will be subject to a higher failure rate than single cell batteries. The more cells used, the greater the opportunities to fail and the worse the reliability. Because of production tolerances, uneven temperature distribution and differences in the ageing characteristics of particular cells, it is possible that individual cells in a series chain could become overstressed leading to premature failure of the cell. During discharging, it is even possible for the voltage on the weaker cells to be reversed as they become fully discharged before the rest of the cells resulting in failure of the cell [2]

Cell balancing is considered when multiple cells in a battery pack are connected in a series. Cell balancing is not needed in a parallel connection of cells, since this configuration is self-balancing. Battery pack cells are balanced when all the cells in the battery pack have the same matched voltage per cell while in a fully charged or discharged state. If one or more of the cells in a pack are not matched then the battery pack is not balanced. When the cells in the battery pack are not balanced the battery pack has less available capacity, since the capacity of the weakest cell in the series string determines the overall pack capacity. In an unbalanced battery pack, during charge time, one or more cells will reach the maximum charge level before the rest of the cells in the series string. During discharge, the cells that are not fully charged will be depleted before the other cells in the string; it appears as a weak cell [3].

3. Satellite EPS Block Diagram

EPS is composed of three main stages; the solar arrays with its power regulation stage, the management and control stage and the storage subsystem stage. The regulated bus voltage can be classified for different satellites missions as follows: typically 28 V on scientific satellites and 50V, 70V or 100V on large communication satellites. The battery stack under study is a NiCd battery consists of 22 series cells where the nominal capacity of each is 8Ah [4, 5].

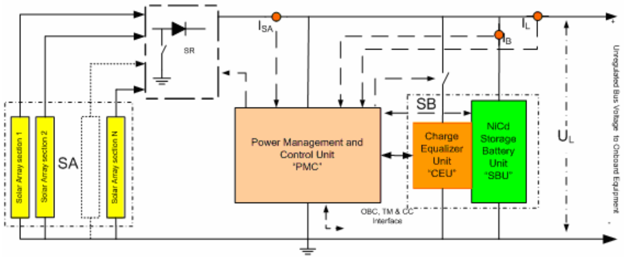

Figure 1, Block diagram of the proposed Micro-satellite EPS (OBC stands for On-Board Computer, TM stands for Telemetry, and CC stands for Control Commands)

4. Purpose of Cell Equalizing

Cell Balancing extends battery life time and improves its performance during the whole satellite run time enabling the voltages on the battery cells to be balanced during the charging/discharging process.

5. Cell Equalization

To provide a dynamic solution to the imbalance problem which takes into account the ageing and operating conditions of the cells, the cell equalization scheme is used to prevent individual cells from becoming overstressed. These systems monitor the State of Charge (SOC) of each cell, or for less critical, low cost applications, simply the voltage across, each cell in the chain. Switching circuits then control the charge and/or discharge applied to each individual cell in the chain during the operating process to equalize the voltage level on all the cells in the pack [2]. Stephen T. Hung, et, al., have reports that, The need to minimize battery degradation by maintaining cell uniformity is the motivation for using a dedicated control mechanism whose purpose is to equalize charge between cells. This charge equalization works as an inner servo-level control system that augments an outer-loop state-of-charge process control, which serves as a strategic supervisor. Figure 2 shows the topology of this two-level control [6].

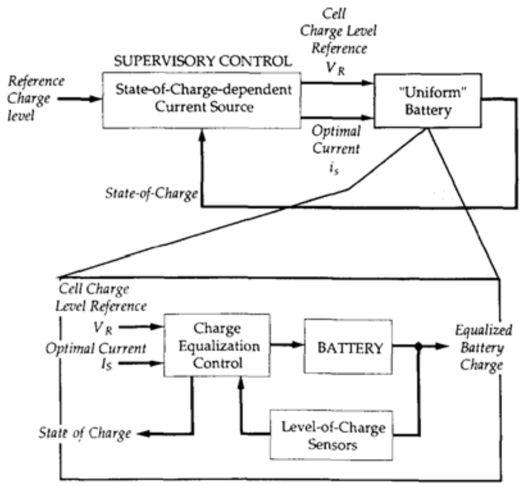

Figure 2, topology of charge equalization by two-level control mechanism

6. Types of battery Charge Equalizing

Stephen W. Moore, Peter J. Schneider [7] and power-designer [8] have reported that, the individual cells equalization approaches can be divided to two main techniques dissipative and non-dissipative techniques.

6.1. Dissipative Equalization Techniques:

The simple technique is dissipative resistive shunts that act to equalize the battery cells in a stack by using bypass resistive shunts across each cell/module. Another two types is used in a dissipative technique named as: Individual cell equalizer (ICE) and end of charge cell balancing or charge shunting, showing in Figure 3, Figure 4 and Figure 5.

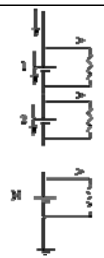

Figure 3, Dissipative resistive shunt

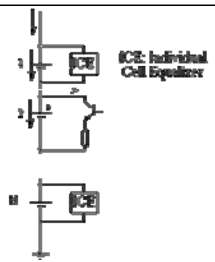

Figure 4, Individual cell equalizer (ICE)

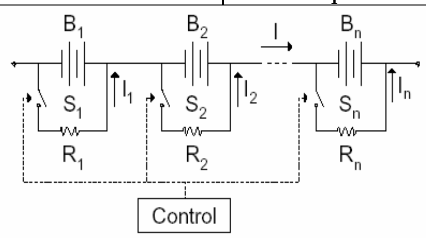

Figure 5, charge shunting

6.2. Non-dissipative Equalization Techniques:

6.2.1.Charge Shuttling:

Charge shuttling cell balancing mechanisms consist of a device that removes charge from a selected cell, stores that charge, and then delivers it to another cell. There are several embodiments of charge shuttling schemes. This technique is applied to cell-to-cell equalization level or to a battery stack (multiple series cells together) to battery stack level. The most disadvantage of this technique is the *higher time constan*t of the capacitor charge/discharge as well as *lower charge/discharge rates* of the storage battery cells. The most notable being, showing in Figure 6 , Figure 7 and Figure 8;

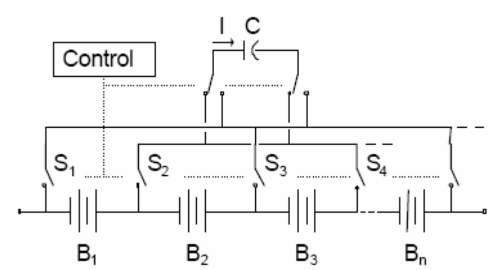

Figure 6, Flying Capacitor Charge Shuttling

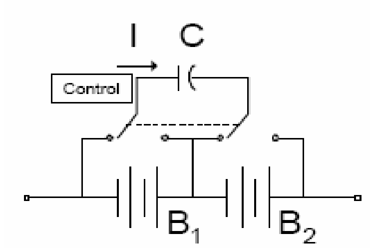

Figure 7, Charge Shuttling Between Two Cell**s**

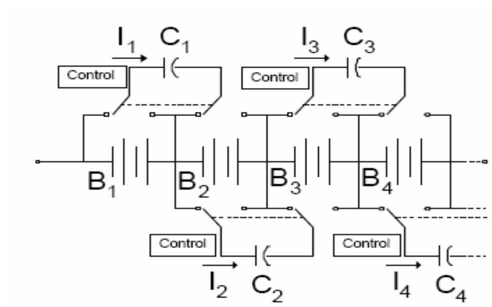

Figure 8, Charge Shuttling with Several Cells

6.2.2.Energy Conversion Techniques:

One approach of achieving charge equalization at high charging rates utilizes isolated dc-to-dc converter modules across each battery cell. Cell balancing utilizing energy conversion devices employ inductors or transformers to move energy from a cell or group of cells to another cell or group of cells. The energy converters techniques used for charge equalization could be listed as follows:

- *Switched Transformer*, Figure 9 ,
- Charge equalization using isolated flyback dc-to-dc converters, Figure 10
- Charge equalization using bi-directional isolated flyback dc-dc converters, Figure 11
- *Shared and Multiple Transformer*, Figure 12, Figure 13
- Charge equalization using a centralized forward converter with a multi-winding transformer, Figure 14 Current diverters using forward or flyback converters with a centralized multi-winding transformer,

6.2.2.1. Analysis of Energy Conversion Techniques

The most effective dynamic equalization is the energy conversion from strong cells to the weak cells techniques as showing from Figure 9 to Figure 14. Theses dynamic techniques can be listed bellow:

- **Switched transformer type**, it is working only in charge mode since the weakest cells can accept more energy compared to others.
- **Charge equalizing using isolated flyback DC-DC converters**, this approach is most suited for large battery systems where a group of cells/modules have a dedicated dc-dc converter. When the voltage of a given module exceeds a preset voltage level, the excess energy is transferred back to the battery bus thus allowing its voltage to be precisely regulated. This approach is working only in battery discharge mode.

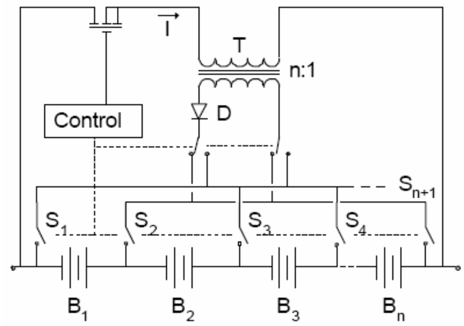

Figure 9, Switched Transformer

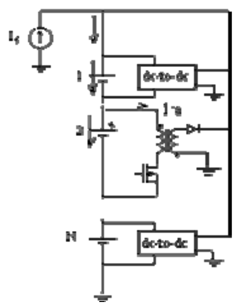

Figure 10, Charge equalization using isolated flyback dc-to-dc converter

- **Charge equalizing using isolated bi-directional flyback DC-DC converters**, this approach is quite similar to the previous one while the energy can be transferred from battery stack (group of cells) to the bas and vice versa, so it working in both charge and discharge modes of the battery. It should be mentioned that a dedicated control is used for each isolated flyback DC-DC converter in both uni-directional and bi-directional techniques.

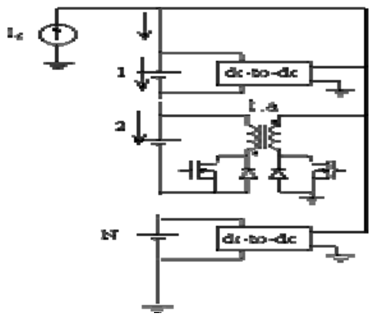

Figure 11, Charge equalization using bi-directional isolated flyback dc-dc converters

- **Shared transformer,** this approach has the same function of isolated flyback DC-DC converters but it uses only one transformer with multiple secondary outputs. It works only to help the weak cells in its discharging mode of operation.

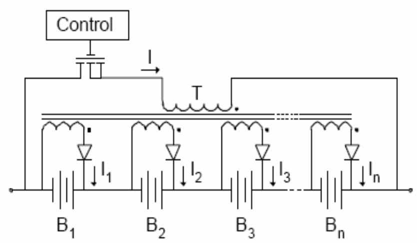

Figure 12, Shared transformer

- **Multiple transformers,** this approach has the same function of shared transformer DC-DC converters but it uses an isolated transformer for each battery cell. It works only to help the weak cells in its discharging mode of operation also. The common since between the shared and multiple transformer techniques is the control logic. They use only one control switch on the transformer(s) primary side.

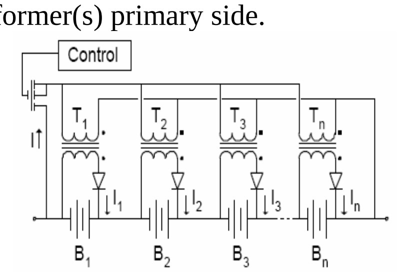

Figure 13, Multiple Transformer

- **Modified Multiple transformers,** this approach has the same function of multiple transformer DC-DC converters while one transformer is use for each two battery cells. The number of transformers will be one half, but the power of each transformer will be double of used one in multiple transformer technique.

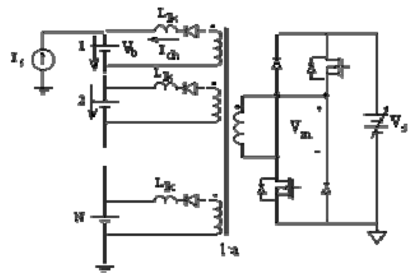
Figure 14, Charge equalization using a centralized forward converter with a multi-winding transformer

- **The other two types are;** current diverters using flyback and forward converters with a centralized multi-winding transformer. It minimizes the required components, but the control is so complex.

The recommended two active energy converter methods are the switched transformer and the shared transformer.

7. Proposed Charge Equalization Unit

The passive type is not a candidate technique especially in space application because of the critical design of the components size and volume as well as cost since the components is sized to meet the requirements of average values of power budget.

The flying capacitor technique is applicable only in small power rating systems as it may be by relevant to the geostationary applications since the charge-discharge duration is suitable with charge equalizing system with flying capacitor relative large time constant. So, in small EOS application where the charge/discharge cycle duration is less than two hours, the energy conversion technique is the preferable CEU technique because of energy saving as well as fast response. The battery charging routine built in the power management and control device protect the battery cells as well as the bus voltage value 34V doesn't permit the battery cells to be overcharged, for this reason, the used technique will be applied only while the battery is in the battery discharging mode. Shared transformer technique is the most candidate system for the following reasons:

- It is the most energy saving technique,
- Minimizing of required components compared to others,

- It needs a small volume and mass, this advantage meets the requirements of space applications,

To reduce the control complexity, a voltage regulator module will be added between the battery bus voltage which represent the source of energy for the CEU and the shared transformer of the voltage changer stage. The proposed CEU consists of three stages;

- Voltage regulation module (VRM),
- Voltage changer module (VCM), and
- A microcontroller module for the CEU logic of operation.

The prototype of the VRM is a buck DC-DC converter since input voltage varies from 21-34V and output will be regulated at 20V. Two loop controllers are implemented to control the output voltage and current of the regulation stage. *It is planned to use the push-bull topology for the final version of VRM, in this case, the VRM DC-DC converter will be buck-boost one to compensate the limitation of the maximum duty cycle at lower input voltage.* The VCM is designed based on the topology of Push-Pull technique with shared transformer of multiple output channels (22 channels for the 22 battery cells). The VCM have a 20V regulated input voltage and outs 22 channels with a rectified 1.2 volts each.

8. CEU Functional Block Diagram:

Figure 15 illustrates CEU functional block diagram (FBD).

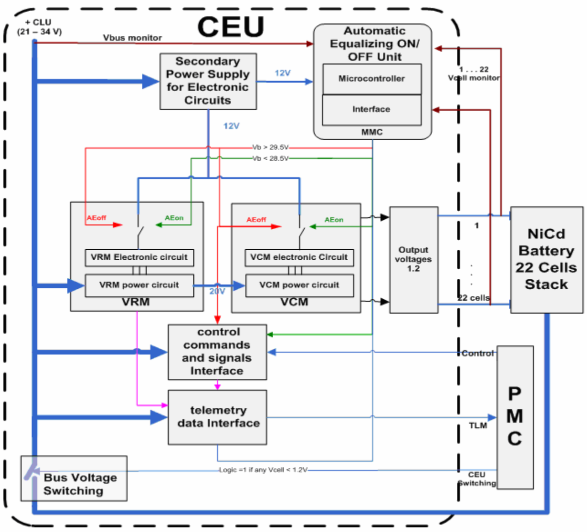

Figure 15, CEU functional block diagram

On the figure, the CEU three main modules; VRM, VCM and MMC with their interfaces are demonstrated.

The operation of the CEU is divided into two modes; preparation for work mode and real working mode. The 1st mode starts when the battery bus voltage gets lower than a specified value ~28.5V and prevented if the voltage get higher again to 29.5V or more. The signals of the first stage are shown on the FBD as AEon/AEoff. This stage just energizes the electrical and electronics circuits of the CEU. In case if any of the battery cells recognize a voltage less that 1.2V, the second stage is energized and support the weak cell(s) that has (have) volts less than 1.2V. The maximum shared current of the single channel of CEU is limited by approximately half of the maximum discharge current of the battery stack (string).

9. Reliability of Charge Equalizer Unit

The Cell Protection/Monitoring and Equalizing circuit contains stand-alone circuitry that monitors each cell individually and intervenes during events of weak cells recognizing situation. Even if the main CEU fails, the safety of the battery pack will not be at risk. The CEU on the other hand, monitors the proper functionality of the Cell Protection/Monitoring and Balancing circuit if needed [9].

An anti-parallel two series diodes are connected with each cell to provide a current path in case of failure of the matting CEU channel and battery cell reaches a revere polarity situation.

10. Simulink Modeling of the CEU Description

The CEU model is built in a Simulink of Matlab 7.0 since the main modules are modeled as follows:

- The VRM is build up as a Buck-Converter topology using BWM controlled by a P-Controller. The feedback signal (voltage) is used to control (regulate) the output voltage at 20V while the input voltage has a random change from 21 to 34V. The input voltage is modeled by a random dc source. Filter is added in the DC link to reduce the output voltage ripples.
- The VCM is simulated as a push-bull topology. The control signals are generated by a PWM generator also. The maximum duration of each signal is limited by 45% from the whole period to avoid overlapping operation between the two switches (MOSFET's) during transition from ON to OFF state and vice versa. A multiple transformer with a center-tap output is used instead of a shared transformer because the unavailability of a transformer with multiple center-tap in the output side (secondary) in the Matlab Simulink library. In the experimental work, a shared transformer with one primary and multiple secondary outputs will be used.

Because of the bus voltage (28V) and the current ratings (5A for each channel and 10A as a summation current from all the active channels), a MOSFET switches are used. The switching frequency is selected to be 30 KHz to meet the electromagnetic compatibility for a small satellites application. Fast Schottky diodes are used in the rectification stages of the output of the VCM. The CEU is tested individually (without the use of battery cells) by implementing a different loading of each channel using different values of power resistances to examine the behavior of the CEU operation.

Figure 16 shows the CEU Matlab model with its VRM and VCM that composed of 6 channels and the simulation results of a resistive loading. The results is presented in graphs, the first one named VRM monitoring shows the following:

1. the random input voltage which varies from 21 to 34V,
2. the PWM control signal of the Buck Converter,
3. the regulated output voltage from VRM, settling time is about 1ms and steady state error is very small while just a P-Controller is used and input voltage bouncing from the minimum to maximum values,
4. error signal of the VRM,
5. VCM AC output voltages which varies from -10V to 10V,
6. The VCM input current.

The second graph which named VCM monitoring shows the current and voltage of each CEU channel, as a lower CEU channel loading as a higher voltage and vice versa. This phenomenon is very clear in the presented graphs. The examination of the CEU shows that it acts as a current source. The actual CEU loading with battery cells simulation results are shown in Figure 17, the VRM monitoring graphs show the same signals as illustrated in Figure **16**, while the VCM monitoring graph the voltage-current curves of the CEU channels at different values of battery cell voltages. The cells of a voltage > 1.2 have a zero sharing currents from its corresponding CEU channels like CEU Ch-3, 22 outputs. The other cells with a voltage close to 1.2V have small values of the sharing current like CEU Ch-2, 5 outputs. While cells with lower voltage have maximum sharing currents values like CEU Ch-1, 4 outputs.

11. Conclusion

A problem of a storage battery operation specially NiCd type and needs for charge equalization process is illustrated in this paper. A review of the most effective CEU is presented and analyzed to show the advantages and disadvantages of its type. The relevant type for space application is estimated as the energy conversion one because of its fast response, lower constant time and efficiency. A shared transformer type is approved to be used because it occupies a small volume and minimum mass which meets the space application.

The CEU is modeled using the Matlab 7.0 Simulink toolboxes. The model is tested alone with resistive loading then tested again with a real battery cells. The results confirm that the CEU acts as a current source during its sharing with weak cells.

Future Work

A research project is currently executed in NARSS - Space Dept., to implement and test A CEU for a reduced battery capacity and circuits rating (scaled down). In the coming publications, the experimental work and the testing results will be presented as a common work with a project team work.

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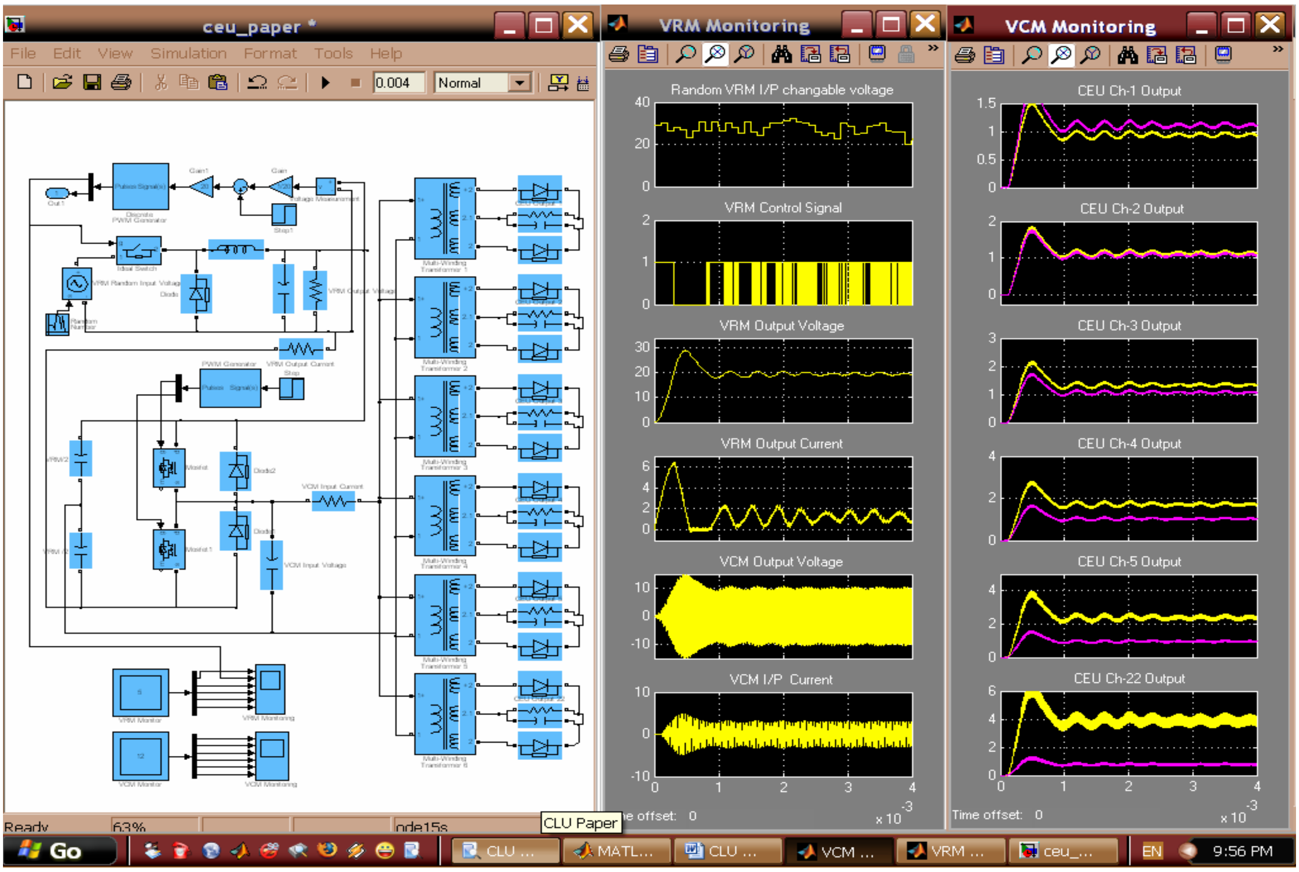

Figure 16, the CEU Simulink model and testing results with a resistive loading

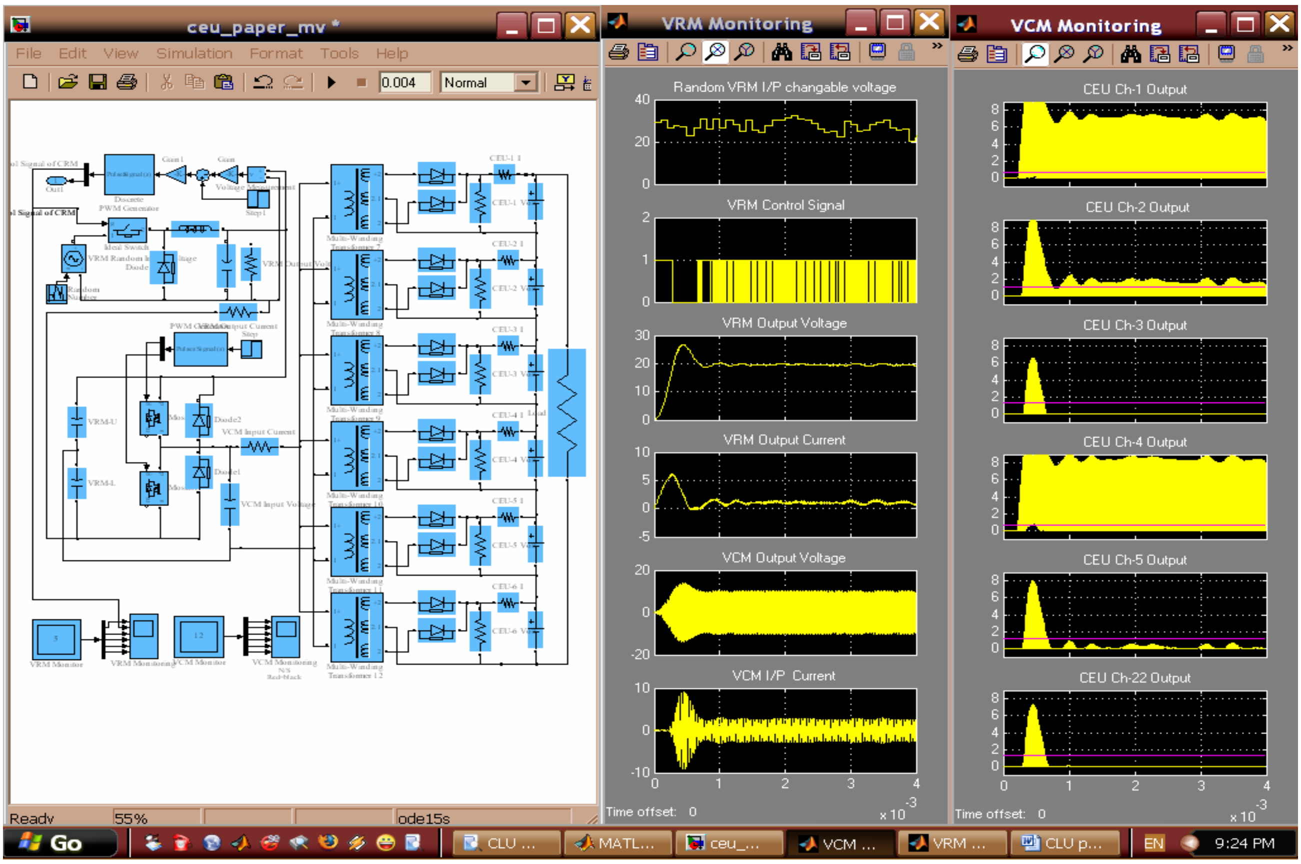

Figure 17, the CEU Simulink model and testing results with a battery cell loading