ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

*(An ISO 3297: 2007 Certified Organization)*

Vol. 3, Special Issue 5, December 2014

# Modularized Combination of Buck Boost and Cuk Converter for Electric Vehicle Lead Acid Battery Cell Voltage Equalization with Feedback

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**ABSTRACT**: The need for a voltage equalizer is principally due to the differences in cell chemistry, temperature gradients along the battery string and the ages of the batteries. Therefore maintaining the charge level on each battery becomes important. This paper analyses the new topology which combines the buck-boost converter and the Cuk converter together which would use only N number of switches for N number of battery in contrast to the (2N-1) switches used by either buck-boost converter or cuk converter. The converter topologies that is a combination of buck-boost and cuk converter without feedback and with feedback are simulated using MATLAB/SIMULINK R2010a. The simulation results show that there is an increase in the rate of equalisation of about 10% with the use of feedback.

**KEYWORDS**: Buck-Boost converter, Cuk Converter, Battery, Electric Vehicle, Battery Equalizer

## I. INTRODUCTION

The various rechargeable batteries available in market are lead acid, nickel cadmium and lithium ion. Their nominal voltages of these batteries range from 1.2V to 3.6V. For High voltage applications such as in Electric vehicles, there is a need of relatively high battery pack. This requires connecting cells in series. As the number of cells increases, parameters such as internal resistance, state of charge, total capacity, internal temperature and degradation level are gradually deviated as the number of the repeated cycles of charge and discharge ,increase. Since the charging current is same for the whole series branch, some of the cells get overcharged, while some others are undercharged, because of the non uniformities. In this case, the undercharged cell cannot be fully utilized while the overcharged cells may get damaged. This leads to the need of battery equalizer schemes to balance cells during charging and discharging of cells.
The requirements of a good battery equalizer are: modularization ,high equalization efficiency ,device voltage stress, fast equalization speed and controller simplicity. Thus we can say that a minimum component count, high efficiency, modularized battery equalizer is highly desired for the intelligent battery management system nowadays. Modularization is defined as the degree to which the system's components may be separated and recombined. Advantages of modularization include ease of adding or subtracting system's components as and when needed which makes system operation easy and comparatively fast. The batteries form the heart of electric vehicles. The electric vehicles are gaining popularity due its advantages of being eco friendly and the fact that it is powered by electricity.

## II. BATTERY MANAGEMENT SYSTEM

A battery is a device for storing chemical energy and converting that chemical energy into electricity. Rechargeable batteries for EVs are lead acid, nickel cadmium and lithium ion battery. A comparison between lead acid battery and lithium ion battery is given in table 1.

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A battery management system is an important part of the electric vehicle (EV) as it protects the battery system from damage, thereby increasing battery life and hence maintains battery system in an accurate and reliable operational condition. The cells, state of charge state of health and remaining useful life are measured by the battery management system.

| Mode / Battery Type | LEAD ACID | LITHIUM ION |
|---|---|---|
| Charging | ▪ Charges very well<br>▪ Passes current to the next cell during equalisation process with little damage | • Overvoltage on a single cell can cause severe damage<br>• Balancing or charging each cell in a string is a solution |
| Discharging | • Tolerates discharging to 0% State of charge (SOC) with some cycle life damage. | • Lithium will have serious damage when discharging below 2.0V. |

Table 1:Comparison of lead acid and lithium ion battery

*a. Battery Equalizer*

A battery equalizer is used to balance the charge level of two or more cells. Here, energy drawn from cell having higher charge is given to the cell with lower charge. High frequency DC-DC converters are used as they are most efficient and inductors, capacitors or transformers form the energy storage elements.The aspects to be considered while choosing a battery equalizer include its cost, manufacturability and efficiency. The equalisation rate is directly proportional to the current of the equalisation system.

*b. Battery Equalizer Design*

The main idea of equalizer is to measure the voltage of every cell that makes up the battery and to set the average voltage of MOSFET switch. MOSFET is connected in parallel with cell of the string so that the equalization takes place during the charging process. The MOSFET used here works in saturation mode as a variable resistance. In addition, the equalisation system also extracts the difference between voltage of a cell and the battery's average value of voltage.

During the battery charging process the cells that has voltage less than the average voltage of the battery needs to be charged so that it reaches the average value as soon as it can in order to attain equal voltages across the cells. The amount of current bypassed through the MOSFET is directly proportional to the value of the difference between the average battery voltage and the voltage of the cell in consideration. Once the cell voltage reaches the average battery voltage the MOSFET is set to the off-state and all of the current that comes to the battery goes through the cell which allows the system to decrease the energy losses. This process of charge equalization is depicted in the figure1.

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In order to determine the amount of current to be balanced the maximum difference between cell voltage and average voltage is set.

$$d_{iff,i} = V_{bat,i} - V_{bat} \quad (1)$$

where,
$V_{bat,i}$ = voltage of $i^{th}$ cell of the battery
$V_{bat}$ = average voltage of the whole battery

And $V_{bat}$ is given by:

$$V_{bat} = \frac{1}{N}\sum_{i=1}^{N} V_{bat,i} \quad (2)$$

Now, when $d_{iff,i} > d_{iffmax}$, all the current is bypassed though MOSFET whereas when $d_{iff,i} < d_{iffmax}$ current is partially bypassed through MOSFET and finally when $d_{iff,i}$=0,no current is bypassed through MOSFET i.e. MOSFET is turned OFF.

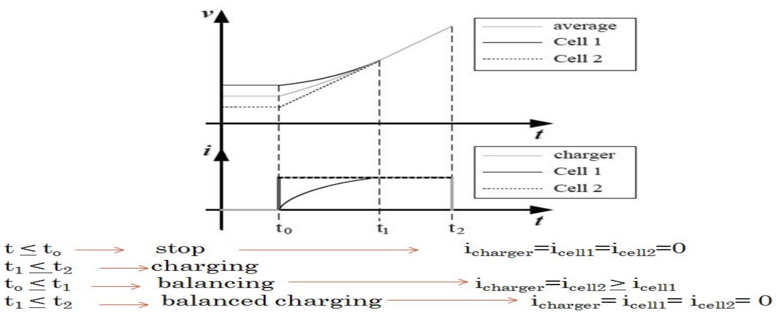


Figure 1 Schematic representation of the battery equalisation process

### c. *Battery Equalizer Configurations*

As is already mentioned that a desirable battery management system has minimum component count, high efficiency and modularized structure. Thus the equalizer can be broadly classified into two types : dissipative or passive type and non-dissipative or active type. It can be further classified as shown in figure 2.

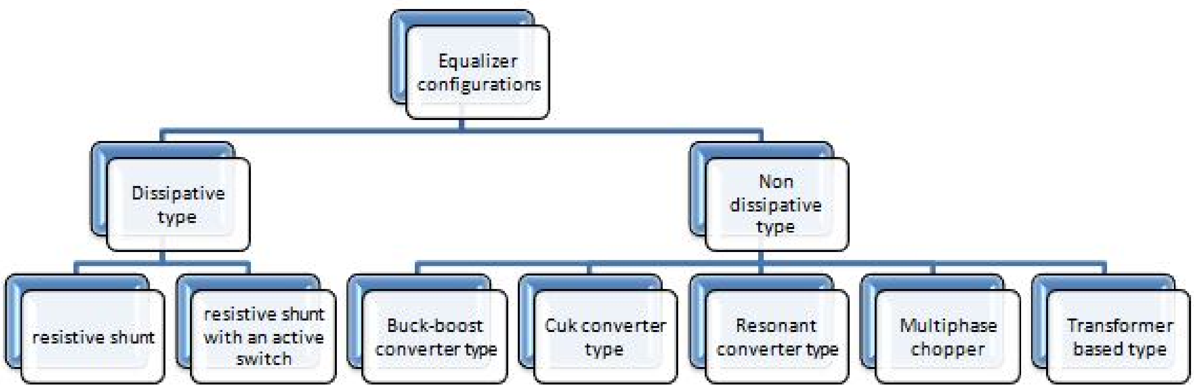


Figure 2 Cell balancing topologies

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In the dissipative type, energy is wasted and extra heat is generated from the dissipated power. One of the dissipative type battery equalizer is shown in figure 3.

Considering the non dissipative types, they either have more than one switch per cell, or they are not modularized due to the transformer or coupled inductor which is a killer for large number of series connected batteries. Multiphase chopper type seems to satisfy with all the requirements, but its own PWM method leads to a high voltage stress, which is equal to the voltage of the whole battery stack, for all the switches and hence is limited to use for small number of battery cell string.

Some of the non dissipative type battery equalizer configurations have been shown in figures 3,4,5 and 6.
Considering the modularization advantage and also low voltage stress a new topology is analysed in this paper. This topology is a combination of buck-boost converter based battery equalizer and cŭk converter with feedback circuit which compares the state of charge of adjacent cells and thereby producing the required PWM switching signal of 50% duty cycle. The addition of feedback circuit enhances the equalisation time. The working of the battery equalisation is discussed further.

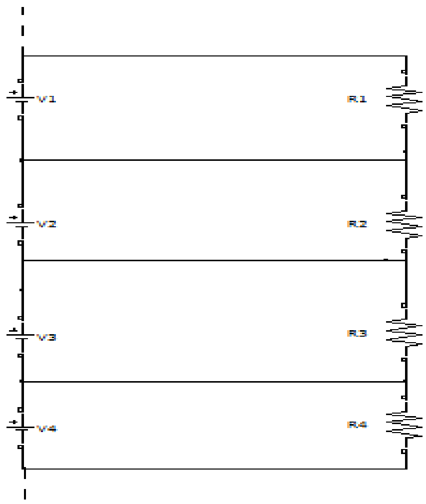


Figure. 3 A dissipative type battery equalizer

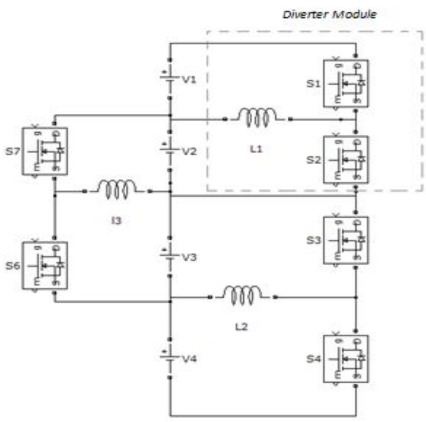


Figure. 4 Buck-boost converter based battery equalizer

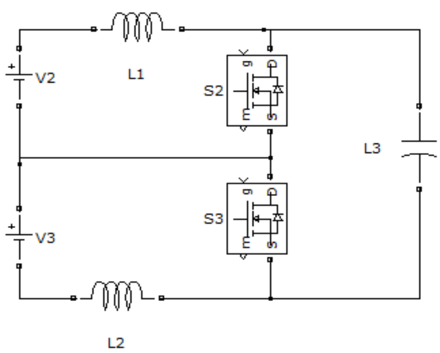


Figure. 5 A cŭk converter based battery equalizer

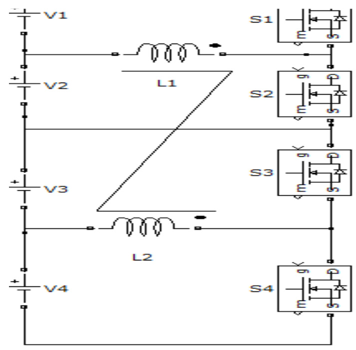


Figure. 6 A magnetic coupled inductor based battery equalizer

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ISSN (Online): 2278 – 8875

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## III. THE BATTERY EQUALISATION TOPOLOGY

The high frequency dc to dc converter which is used for battery equalizer purpose requires negative output voltage instead of positive output voltage. Considering the modularization factor and minimum switch count that is, one switch per cell, a topology which combines a buck-boost converter and a cŭk converter is analysed. It results in relatively low voltage stress across switches. The circuit for the same is given in figure 7. Here only one module is considered for simplicity. The figure8 shows the circuit configuration for 4 cells and figure 9 shows the case for 6 cells. The dotted part can be understood as module A, while the lined part can be thought as modular B. If only one l cell is to be added or removed module A or module B can be added independently with the single cell, depending on the circumstances. Whereas if 2 cells are to be added or removed at the same time, it can be seen as one module.

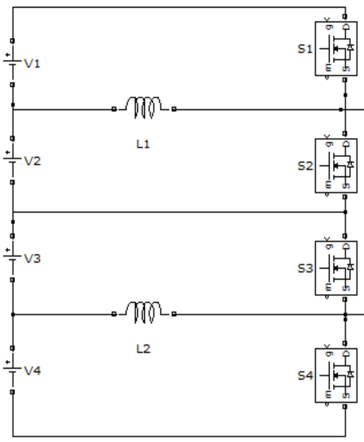


Figure 7: Module A

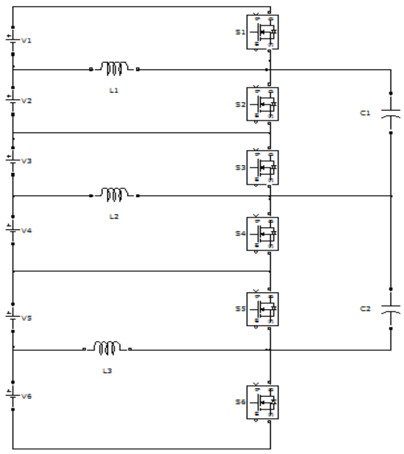


Figure 8: Module B

*a. Operating Modes*

The equalizer has ‘N’ switches; ‘N/2’ inductors ; ‘(N-2)/2’ capacitors . Battery cells 1 and 2 are balanced using the upper traditional buck-boost converter by controlling S1 & S2 with 50% duty cycle, while cells 3 & 4 by controlling S3 & S4 with 50% duty cycle. The battery cells 2 & 3 are balanced using the Cuk converter in the middle by controlling S2 & S3 with 50% duty cycle. Considering the dead time and assuming V1>V2 and V3> V4, there are 2 switching mode.

*1) Switching Mode I*

Here the state of charge of battery cell 1 and cell 2 are compared and it is detected that state of charge of battery cell 1 is greater than that of battery cell 2 (as V1>V2 was assumed) and switch 1 and switch 3 are turned ON(shown) and switches 2 and 3 are OFF(not shown). Here the battery cell 1 gets discharged and the battery cell 2 gets charged through by the energy transfer capacitor through inductor and switch 3. Battery cell 3 is discharging through the second inductor, L2.while battery 4 is neither getting charged or discharged.
The equivalent circuit is shown in figure 10.

2) *Switching Mode II*

Here the state of charge of cell 2 and 3 and cell 3 and 4 are compared and it is detected that the state of charge of battery cell 3 is greater than cell 4(as, V3>V4 was assumed) During this period of time, battery cell 2 is being charge by L1 through S2. Battery cell 3 is discharging to C through S2 and L2. Battery cell 4 is being charged by L2 through S4.the equivalent circuit is shown in figure 10. Here switch 1 and 3 are OFF (not shown).

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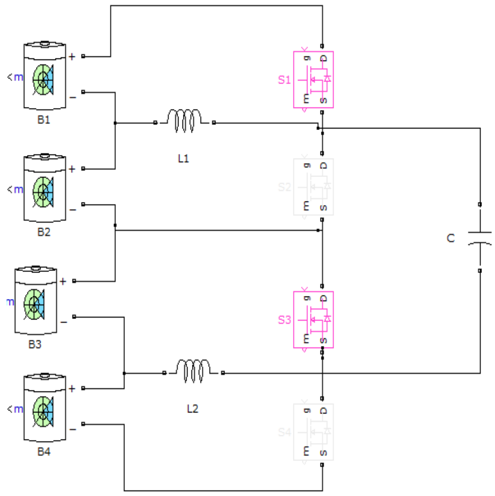


Figure 9: Mode I operation

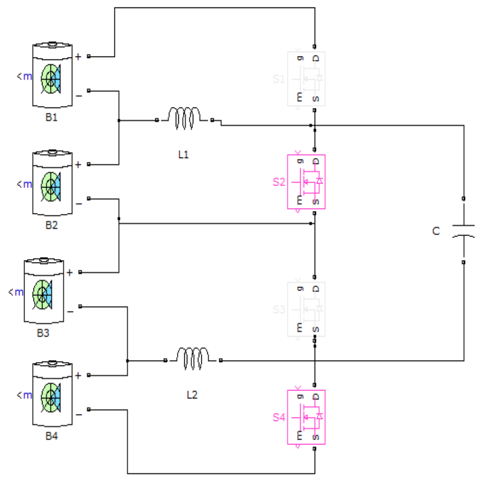


Figure 10: Mode II operation

## IV. SIMULATION RESULTS

In order to show the relevance of the combination of buck boost and cuk converter based battery equalizer circuit, two circuits, one without feedback and one with feedback were simulated in MATLAB/SIMULINK. The feedback circuit consist of a comparator which compares the state of charge of the adjacent batteries. If their state of charge do no match, a reference signal is generated which is used to generate PWM switching pulses. The figure 11 shows the SIMULINK model of the battery equalizer without feedback and figure 12 shows the SIMULINK model of battery equalizer with feedback.

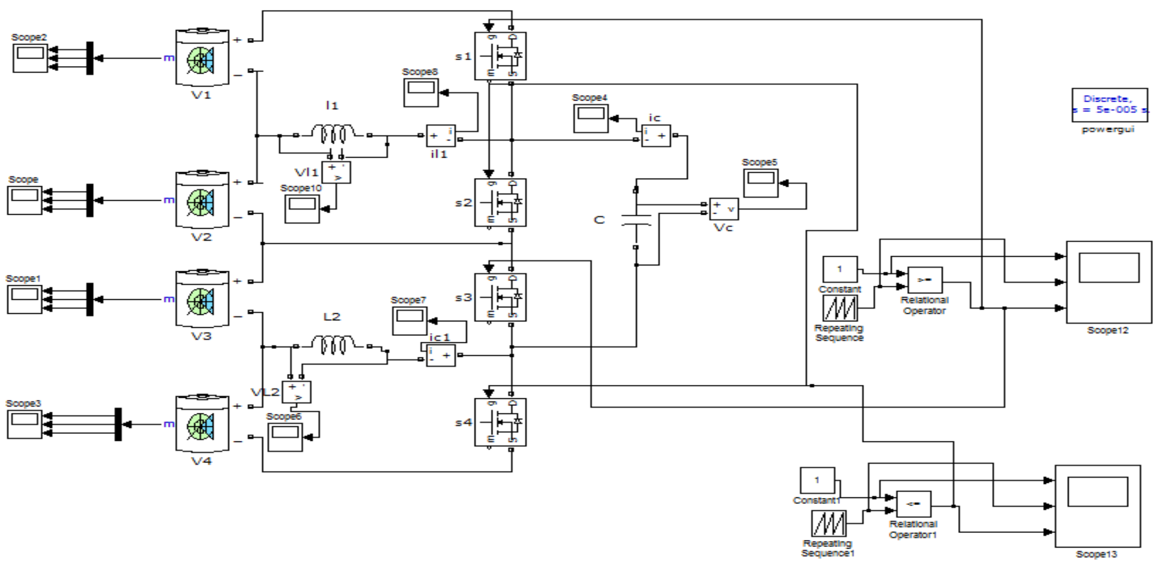


Figure 11: MATLAB/SIMULINK model of the circuit without feedback

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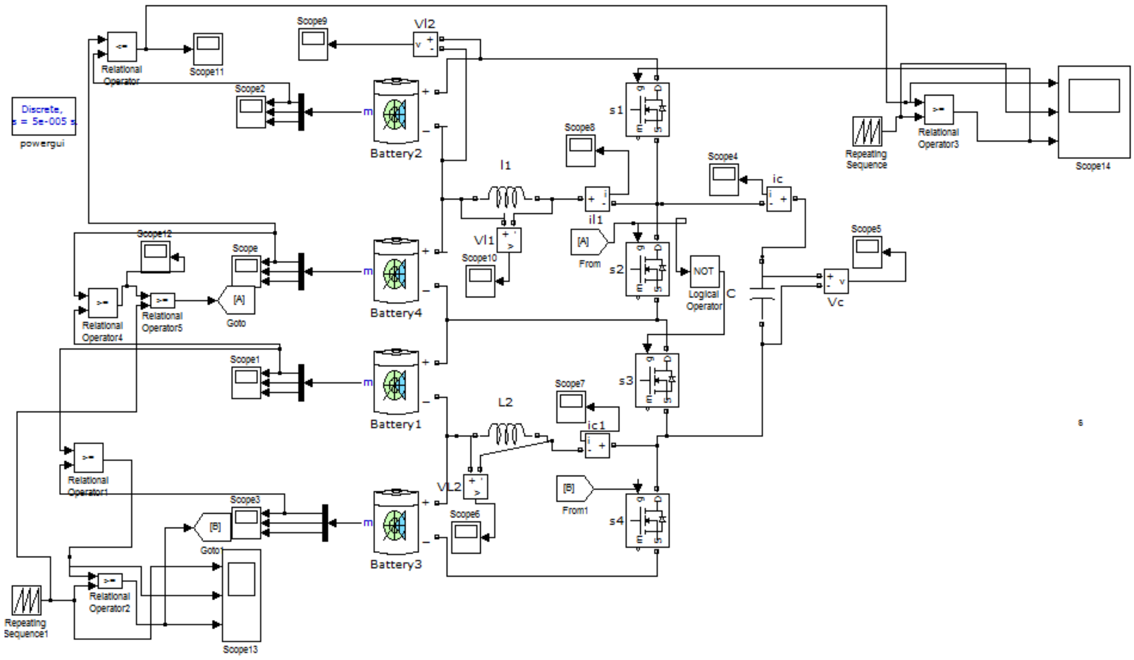


Figure 12: MATLAB/SIMULINK Model of the circuit with feedback

### B. *Simulation Result For Circuit Without Feedback.*

The simulation result show the state of charge of the 4 battery cells over a period of 10s simulation time for circuit without feedback. Figures 13 to 16 show the state of charge of the four batteries over 10 sec simulation time when the battery equalizer without feedback is used. Here the initial state of charge is 90% 88% , 90% and 87% for batteries 1,2,3 and 4 respectively. After 10 sec the state of charge of battery 1 decreases to 89.961 whereas the battery 2 state of

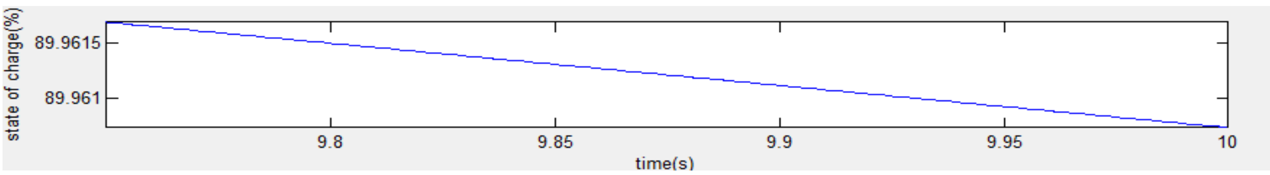


Figure 13: State of charge of battery 1 of the circuit without feedback.

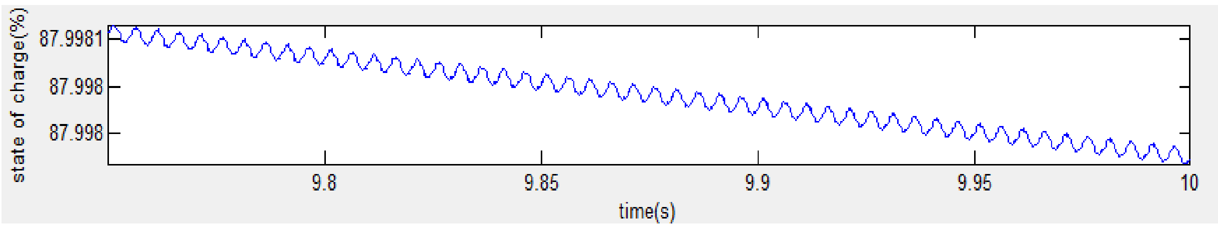


Figure 14: State of charge of battery 2 of the circuit without feedback.

charge also decreases slightly by 0.002% . Likewise battery 3 state of charge decreases by a slight % and battery 4 also decreases.

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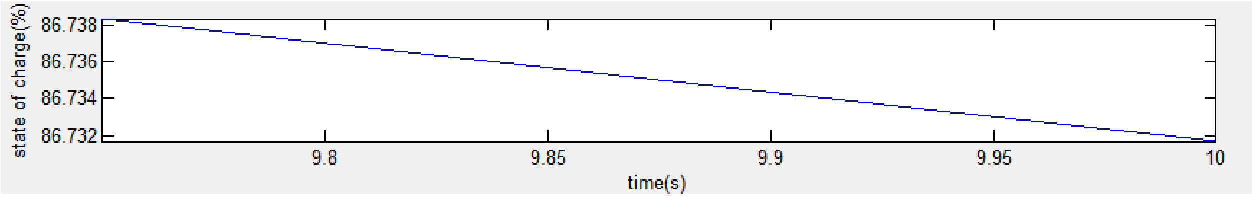


Figure 15: State of charge of battery 3 of the circuit without feedback.

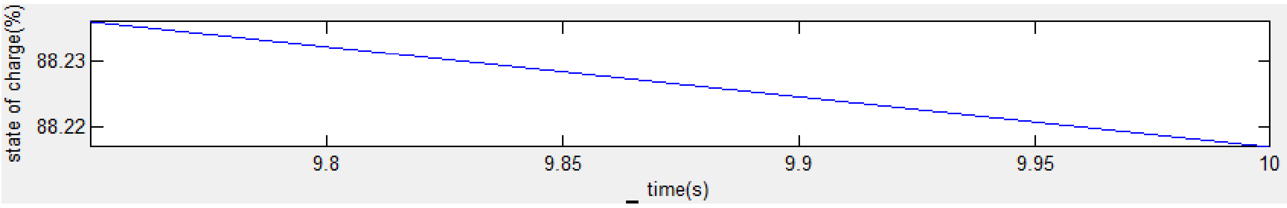


Figure 16: State of charge of battery 4 of the circuit without feedback.

*a. Simulation Result For Circuit With Feedback*

The simulation result show the state of charge of the 4 battery cells over a period of 10s simulation time for circuit with feedback. Figures 17 to 20 show the state of charge of the four batteries over 10 sec simulation time when the battery equalizer with feedback is used. Here the initial state of charge is 90% ,88% , 90% and 87% for batteries 1,2,3 and 4 respectively, same as that used for circuit without feedback. After 10 sec the state of charge of battery 1 decreases to 89.9608 whereas the battery 2 state of charge increases by 0.03% which is actually desired. Likewise battery 3 state of charge decreases by a slight percent and battery 4 also decreases. Thus we see that the use of feedback enhances equalisation rate by 10% .

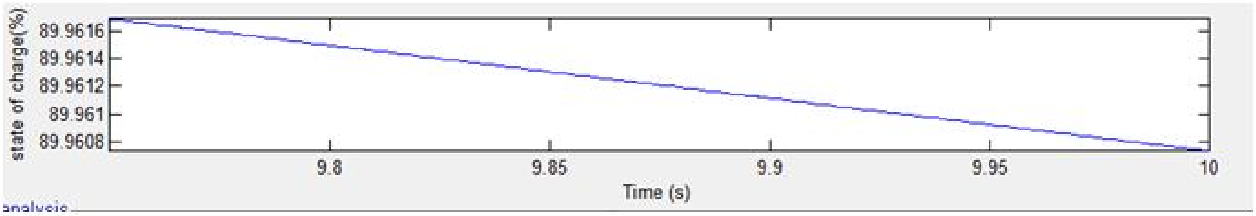


Figure17: State of charge of battery 1 of the circuit with feedback.

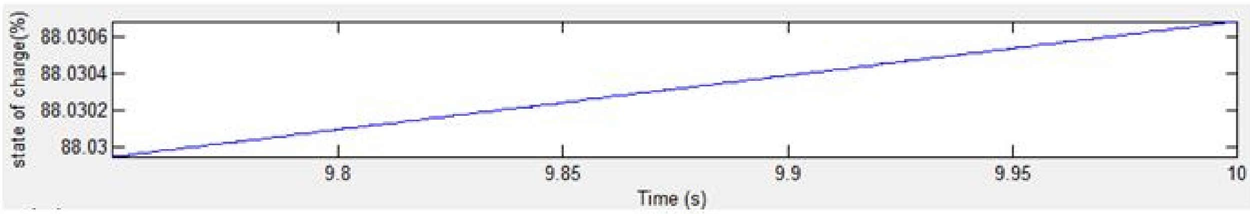


Figure 18: State of charge of battery 2 of the circuit with feedback.

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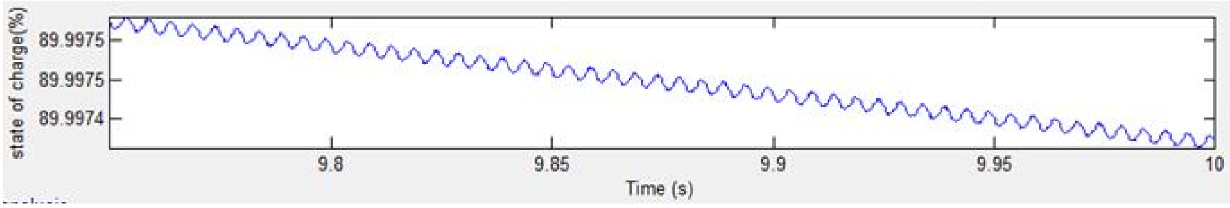


Figure 19: State of charge of battery 3 of the circuit with feedback.

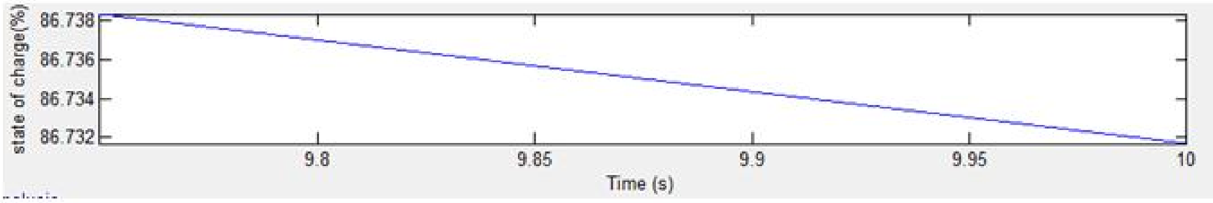


Figure 20: State of charge of battery 4 of the circuit with feedback.

## V. CONCLUSION

The lifetime of the Electric Vehicle (EV) depends on the lifetime of its battery system, so any prolonging in the lifetime of the lead acid battery cells will effect the economic feasibility of the vehicle. Battery cell equalization will reduce the degradation of the capacity of the cells with the time. This is done by transferring the charge from the cells with higher charge (because of the degradation of the capacity the cells will charge faster) to the other cells. This prevents the discontinuity of the charging current and allows all the cells to be charged to its maximum capacity, and as a result will prolong the lifetime of the cells. The modularized combination of buck boost and cuk converter for electric vehicle lead acid battery cell voltage equalization with feedback circuitry was simulated and was compared with its already existing open loop configuration. the simulation results show that for the same period of time charge equalization was faster by 10% . Thus the use of feedback loop enhances the equalisation time, and hence increases the efficiency.

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