# RelBat: A Reliable Battery System Towards the Realization of Sustainable Electronics

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***Abstract*—This paper presents a battery simulation flow and system to help design engineers to simulate battery arrays, demonstrate their characteristics, their modes of operation and the results of their implementation. As an example application, a reliable battery is presented which consists of battery cells, a cell switching circuit, a battery cell array manager and a system safety manager. This is useful for managing the existing energy infrastructure in an efficient and smart manner such that batteries last for a longer time. The RelBat system is built on a management system which performs its management activities by protecting the battery from operating outside its safe operating area, monitoring its state, calculating data, reporting the data and controlling its environment (modifying the temperature). Related work has focused on a battery model system which adapts to the current profile of the device, while this research focuses on the deployment of smarter batteries to self-manage lifetime.**

***Index Terms*—Portable Electronics, Smart Battery, Reliable Battery, Design Simulation, Simscape® Modeling**

## I. Introduction

Energy efficient system design and battery aware system design go hand in hand for sustainable portable electronics [1]. Energy efficient system design aims at making the system design energy or power efficient. On the other hand, batter aware system design tries to have a power dissipation profile that can best match the battery power delivery profile.

The overall system's capability, performance, and usage profile along with the ampere-hour energy rating of the battery in a portable consumer electronics determines the life of a battery [2]. However, safety of the installed batteries in portable devices is still a major concern [3].

The main contribution of this paper is to illustrate a method of managing battery resources smartly and efficiently such that performance of the battery during use is enhanced but we are also able to prolong the life of the battery as well. The importance of using Simulink® to model this system (called RelBat), is its ability to model hierarchical subsystems with predefined library blocks, and to simulate the dynamic behavior of the system.

The rest of the paper is organized as follows. Section II summarizes the contributions of this paper. Section III discusses related prior research on smart battery and Simulink® modeling of similar scope. Section IV presents a specific reliable battery architecture. Section V presents the design and simulation flow proposed in this paper. The modeling and simulation results are presented in Section VI. The paper discusses conclusions and future research in Section VII.

## II. Contributions of this Paper

This article has the following novel contributions: (1) Demonstrates the modeling of RelBat, which is composed of multiple cells and two management units. (2) Demonstrates the implementation of a cell selection algorithm that provides monitoring and cell selection capabilities. (3) Demonstrates the implementation of a permanent emergency system and/or cell shut down by a system safety manager that also utilizes the cell selection algorithm. (4) Implements and demonstrates the model using Simulink®.

## III. Related Prior Research

A prior research for intelligent battery is titled Reliable Battery Management System for Electric Vehicles [4]; it addressed various challenges in electric vehicle battery systems and components. Another prior research for smart battery is titled Towards Smarter Battery Design [5], which was implemented using SystemC but did not take into consideration the fact that battery state could degrade such that battery could be rendered permanently unusable and could also cause damage to the load. In the present work, this deficiency is addressed with the introduction of a System Safety Manager, as shown in Fig. 3. In [6], the focus is on battery pack management. Here the design and test of battery pack simulator (BPS) was implemented using Simulink®. The testing of battery management systems is done by taking into account the characteristics and environmental conditions of individual cells, such as capacity or ambient temperature which can be adjusted in order to examine the unbalance in battery pack on the functioning of the Battery Pack Simulator (BPS).

## IV. Reliable Battery Architecture

This research has focused on transferring the responsibility of energy management in the battery to the Battery Cell Array Manager (BCAM). Lithium cells have been modeled using Simulink® to emulate the behavior of a real cell. the system, as shown in Fig. 1, consists of battery discharge management, current flow management and battery state management. The proposed architecture involves a cell array, a cell switching circuit (CSC), the BCAM and a System Safety Manager (SSM) [5]. The battery cells discharge to the load based on the directions of the switching circuit which in turn receives and executes instructions from the BCAM and the SSM. The SSM supersedes the BCAM, i.e. regardless of the instructions from the BCAM, the SSM instruction can override it and shut down the CSC to ensure safety in the entire system.

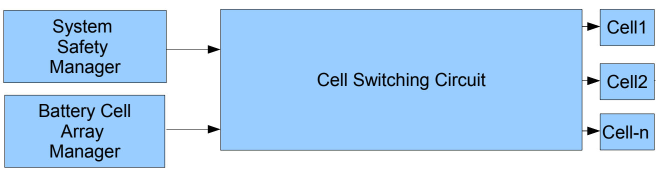


Fig. 1. Proposed Reliable Battery System Architecture.

The algorithm for the battery cell array manager selector is given in Algorithm 1, while the algorithm for the safety manager is given in Algorithm 2.

**Algorithm 1** Proposed Cell Selector Algorithm.

**Data:** Input = Load Current(I), Voltage/State of Charge(V) Output = g1, g2, and g3
**Result:** Assign threshold for I and V to g1, g2 and g3
initialization **while** *I and/or V(SoC) equals and/or less than(assigned threshold)* **do**
  g1, g2, and g3 equals 0 (gate opens) **if** *not* **then**
    go to next section current section becomes this one
  **else**
    g1, g2, and g3 equals 1 (gate closed)
  **end**
**end**

**Algorithm 2** Proposed Cell Disconnect Algorithm.

**Data:** Input = Voltage/State of Charge(V) Output = c1, c2, and c3
**Result:** Assign threshold for V to c1, c2 and c3
initialization **while** *V(SoC) equals and/or less than(assigned threshold)* **do**
  c1, c2, and c3 equals 0 (gate opens) **if** *not* **then**
    go to next section current section becomes this one
  **else**
    c1, c2, and 3 equals 1 (gate closed)
  **end**
**end**

The intelligent battery system exploits the charge recovery effect of cells combined with a cell scheduling scheme to deliver the required load to the system while enhancing battery lifetime. A RelBat system is built on a management system which manages it by protecting the battery from operating outside its safe operating area, monitoring its state, calculating data, reporting the data and controlling its environment (modifying the temperature). Previous related work focused on a battery model system which adapts to the current profile of the device, while this research focuses on the deployment of smarter batteries to self-manage lifetime. The Battery Cell Array (BCA) structure consists of the following:

- Reliable Battery Cells (RelBat) Cells organized as a collection of banks.
- Cell Switching Circuit (CSC) Supports current sourcing without incurring significant losses.
- Battery Cell Array Manager (BCAM) Monitors cell status and ensures safety of the BCA.

## V. Proposed Simulink® based Modeling Flow

Simulink® has been used as the modeling and simulation framework due to its obvious advantages including availability of a good library for system modeling [7]. The first step was to determine the various devices and components and ensure specifications are met. Then the physical design was made for the entire system. The next step was to design and create each subsystem. The Battery Cell Array subsystem was created and tested. If it passed the tests based on the required specifications and type of battery cell that was being emulated, the design proceeds, otherwise the same step is iterated until the BCAS is finalized. This process was followed for the CSC, BCAM and SSM modules. The entire subsystem was integrated and again tested to ensure that the system is switching between each battery cell whenever the BCAM determines that the threshold has been met based on the state of battery, voltage, and current flowing in the system. Also the SSM was tested by inputing an unacceptable battery state to ensure that it indeed overrides the decision of the BCAM to ensure the safety of the entire system.

## VI. Modeling and Simulation Results

In Fig. 2 the state of charge and depth of discharge simulation results are shown. A more sophisticated and intelligent circuit breaker, as shown in Fig. 3, was selected to work with the SSM. As also shown in Fig. 3, the battery is being discharged, and once the threshold is reached, the cell selector algorithm in the BCAM will switch the load to a different cell. The cell disconnect algorithm that is functioning in the SSM will override the BCAM in a situation where there is potential danger to the battery, the entire system and or the individual(s) operating the system. In Fig. 4 simulation results for the cell selector algorithm which is transferring the load from one cell to another due to threshold being attained, are shown. Fig. 5 shows the voltage attenuation with time.

In Fig. 6, a larger battery has been split into 3 cells of the same combined capacity. Cell1, cell2 and cell3 are connected in series/parallel combinations to the switching circuit as

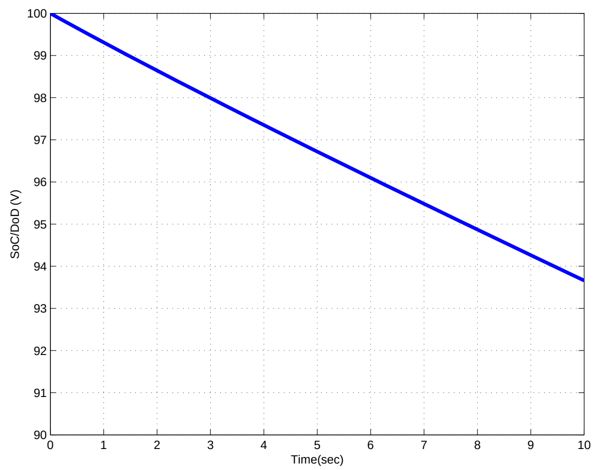


Fig. 2. Simulation Results - State of Charge and Depth of Discharge.

shown in Fig. 3. The load will receive its energy from each of the three cells based on the decision of the BCAM.

Fig. 7 shows how the performance of Lithium Ion batteries deteriorates as the operating temperature decreases. For both high and low temperatures, the further the operating temperature is from room temperature, the more the cycle life is degraded.

Likely savings based on the national average are shown in Table I.

TABLE I
AVOIDED COST OF EMISSIONS [8].

| Emission | Avoided Costs |
|---|---|
| $CO2$ | \$29.01/ton |
| PM | \$16.91/pound |
| $NOx$ | \$0.69/pound |

TABLE II
ENVIRONMENTAL COST SAVINGS OF UTILIZING THE BCAM FOR LOAD SWITCHING AND BATTERY MANAGEMENT (ELECTRIC VEHICLE, EV).

| Output | Traditional costs | Costs savings |
|---|---|---|
| $CO_2$ | 8,887grams/gallon(gasoline) | \$0/gallons |
| \$/100miles | \$15.9/100miles(gasoline) | \$3.48/100miles(EV) |

In previous proposed works ( [5], [9]) smart management of battery energy was presented by utilizing a cell switching circuit and battery manager to transfer the load to a battery based on the cell scheduling algorithm. However, these works did not take into consideration the fact that the batteries could be degraded due to over discharge and over utilization. Also the safety of the entire system was not considered. In this paper we have taken into consideration in the Battery Management algorithm the life cycle of the battery and have taken steps to limit the number of times the load utilizes the cell again. Also the need not only to safeguard the battery, but the entire system (which includes the battery and the load/device), and the user, is taken into account.The System Safety Manager, which acts like a supervisor was introduced. The management algorithm in the SSM has the ability to override the BCAM in situations where the cells, the load/device and/or the user are endangered due to malfunctioning of part or the entire system. The SSM shuts off the current supply permanently to a specific bank or all the banks if and when the need arises.

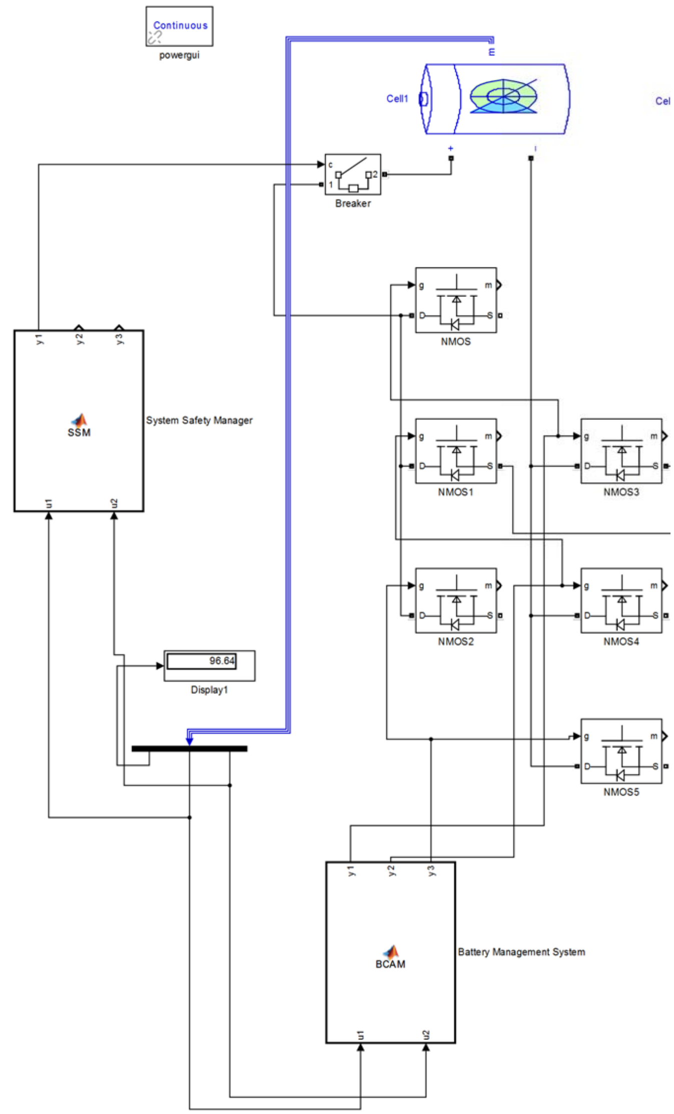


Fig. 3. Overall System Block Diagram.

## VII. CONCLUSIONS AND FUTURE RESEARCH

The proposed practical implementation of this research is in portable devices, like laptops, tablets, cell phones, etc. The idea is that by transferring the load to each cell when the previous cell in use reaches a threshold (state of charge, current flow, temperature and/or voltage), we are able to prolong the life of the battery and also there is opportunity to charge the discharged cells while utilizing another cell. This provides the opportunity of preventing the battery from overheating and also from charging for too long because the cell is not in use while it is being charged.

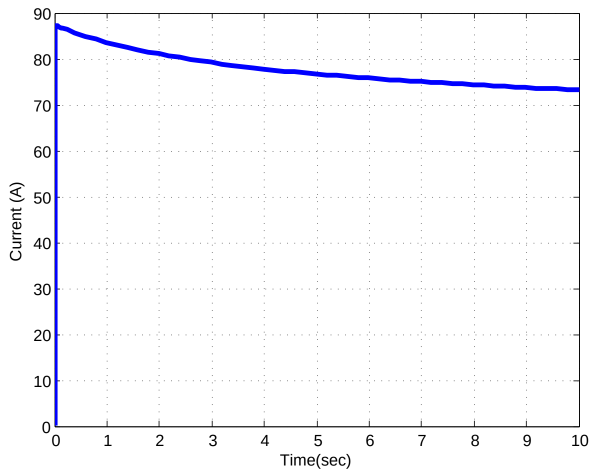


Fig. 4. Simulation Results - Current utilization by the load.

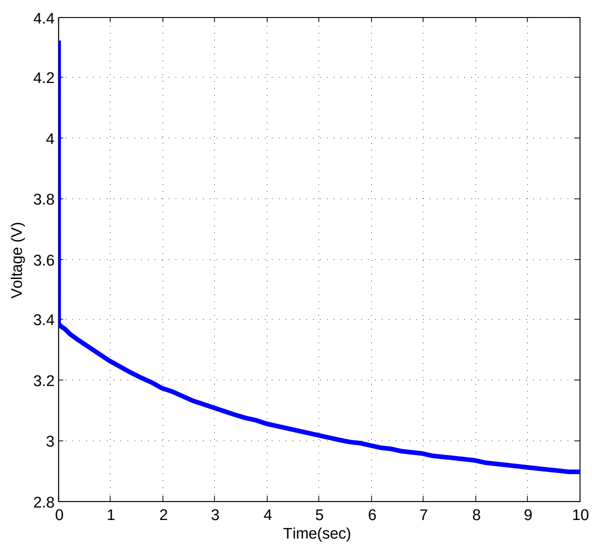


Fig. 5. Simulation Results - Voltage Attenuation.

The Simulink® proposed implementation of the RelBat system provides researchers with the opportunity to mimic a real life situation. The RelBat proposed system consists of the cell arrays, the switching circuit, the battery cell array manager and the system safety manager, all of which work together to deliver a smart energy utilization and management strategy. This research focused on Simulink® modeling and introduced an independent safety system that can override the instructions of the battery cell array manager to ensure safety of the system and individuals using the system. Also the focus was on energy

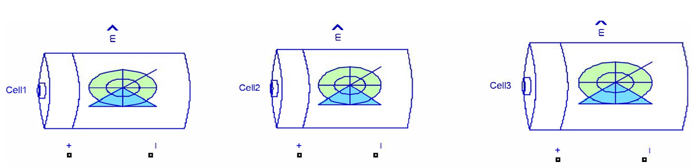


Fig. 6. Cell Array - Lithium-Ion Battery Cells.

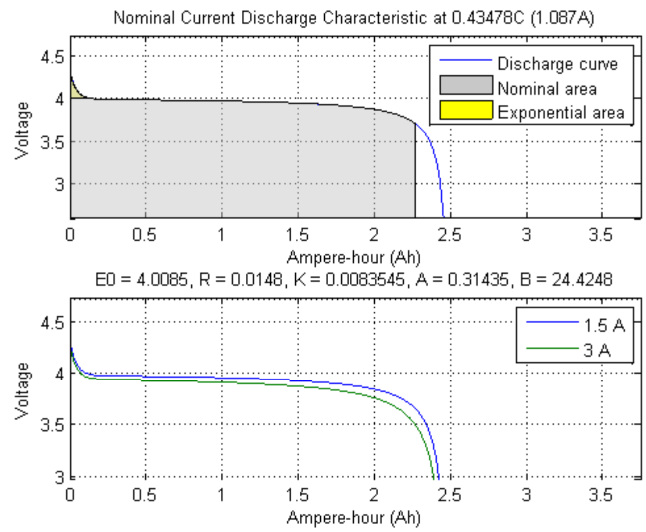


Fig. 7. Lithium-Ion Battery Discharge Characteristics.

use and discharge management. Future research will address recharge management. The introduction of a solar charing system/panel will be a realistic and smart approach for this research because it will enhance the portability which is the main focus in this research.

## ACKNOWLEDGMENTS

An early implementation of this paper was presented in [10].

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