State of Charge Indicator (SOCI) Design for Li/CFx Battery

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***Abstract*— The lithium polycarbon monofluoride (LiCFx) battery is sensitive to a number of dynamic environmental conditions, such as the ambient temperature. The flat discharge profile typical of the LiCFx battery current State of Charge Indicator (SOCI) technology poses a challenge to obtaining accurate estimates using conventional, voltage-based SOCI technology.**

To monitor this LiCFx discharge state of charge, an Artificial Neural Network (ANN) algorithm provides a nonlinear solution. The underlying technology is charge counting with nonlinear ANN-based compensation for temperature, rate of charge, and charge history. This paper explains the design of an ANN algorithm and its training. Measurement error for this ANN-based solution is estimated to be within 2-3%. Initial cost estimates are under USD $30 in bulk quantities. Drain on the battery is less than 1.5% per year, with a 10-year shelf life for the SOCI. This paper describes the performance of a sequence of prototypes based on this ANN technology. Appropriate testing results support the accuracy estimate.

***Index Terms*— LiCFx, Lithium batteries, Artificial Neural Network, State of Charge, Embedded System**

INTRODUCTION

SEVERAL batteries provide a reliable source for the numerous hand-held devices utilized throughout the world today. The cell provides a relatively flat voltage discharge curve for a majority of the discharge profile, for a continuous discharge current at a specific temperature shown in Figure 1.

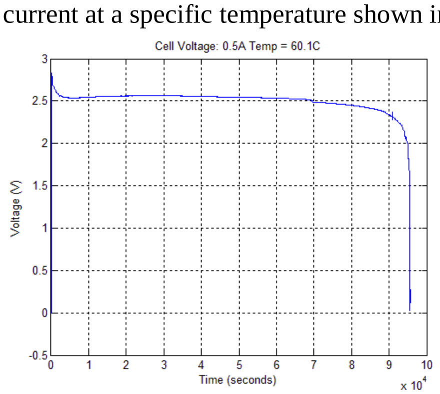

Figure 1: Discharge curve of D-sized LiCFx cell [1,2].

The discharge curve of battery was taken at 60°C and 0.5A. Moreover, the flat discharge curve, with a sudden drop toward the end, makes it challenging to indicate the SOC of the battery accurately.

Thus, the flat discharge curve of the battery, along with the nonlinear change in battery performance due to variation in temperature, proves difficult to use Colomb Counting alone to calculate the SOC.

For the LiCFx battery, in order to increase the accuracy and accommodate the flat discharge curve of the battery, an Artificial Neural Network (ANN) is being used as the main evaluator.

SOCI DESIGN OVERVIEW

The SOCI has been designed to take voltage, discharge current and ambient temperature inputs from the battery count. These values are collected from the respective sensors that are present on the board (shown in Figure 2).

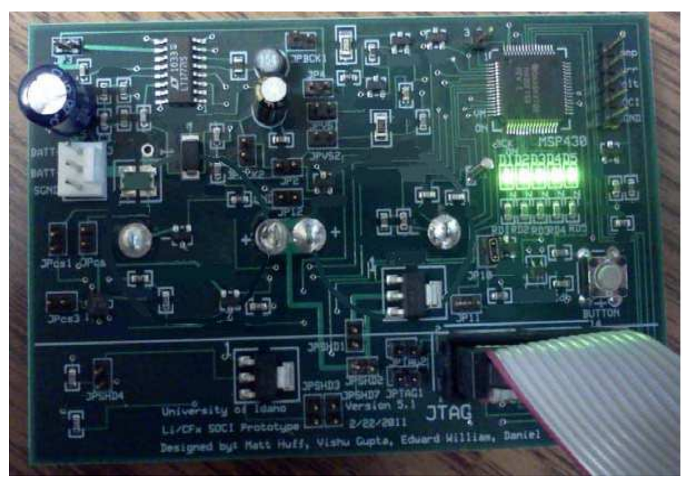

Figure 2: SOCI prototype board [1]

The output of these sensors is sent to the MSP430 series microcontroller, where all of the evaluation is performed. The data is converted using the A/D converter on the MSP430.

This converted data is sent to the ANN, which uses these parameters to calculate the SOC along with the usual SOC calculating method.

This display is read from left to right, and the number of lit LEDs indicates the range of SOC of the battery. Table 1 presents the range of values for each LED.

Table 1: LED Indication of SOC of Battery [5]

No. of Lit LEDs	% of Battery Capacity Remaining
5	90% - 100%
4	70% - 89%
3	50% - 69%
2	30% - 49%
1	10% - 29%

The designed SOCI was required to meet the following specifications [5]:

- Accuracy > 95%
- User-activated LED display using 5 LEDs [5]
- Operation under extreme temperatures (-40°C to 80°C)
- Low cost, small size, low current consumption
- Available sleep mode
- SMBus capabilities

Several prototypes of a SOCI meeting these requirements have been developed. The performance of the SOCI has been improved over the different versions to better meet these requirements.

ARTIFICIAL NEURAL NETWORK

Artificial neural networks (ANNs) are computational intelligence architectures based on biological neural networks. They are capable of "learning" interdependencies and trends in data [5].

The basic unit of an ANN is a neuron, which is functionally similar to a biological neuron and has a set of inputs and produces an output based on those inputs. Thus it creates an interconnected network of neurons that combines to produce an output based on a number of weights, aggregations and comparisons.

An artificial neuron aims to achieve the same goal by using weights and a threshold value, and by producing an output vector for a given input vector. An input vector, which is fed to an artificial neuron, with *n* dimensions can be expressed as:

$$\vec{X} = \{x_1, x_2, ..., x_n\} \tag{1}$$

In an artificial neuron, for each input x_q a weight w_q is assigned. The neuron calculates the weighted sum *z* as:

$$net = \sum_{q=1}^{n} w_q x_q \tag{2}$$

The output of the neuron is governed by the activation function, which acts as a threshold. The output is given by:

$$o = f_s\left(\sum_{q=1}^{n} w_q x_q\right) \tag{3}$$

where $f_s(x)$ is an activation function, and the sigmoid activation function is used typically:

$$f_s(x) = \frac{1}{1+e^{\lambda_s x}} \tag{4}$$

An ANN consists of multiple interconnected artificial neurons, arranged in several layers. The neurons are arranged in layers: one input layer, one output layer, and multiple hidden layers. The neurons in the input layer have the activation function $f_s(x) = x$.

A. ANN First Implementation

The ANN implemented is called a "feed forward" network. This consists of two layers of neutrons, in which one of the layers evaluates the synaptic weight of each input and sums the weights as input for the second layer. The second layer evaluates the weight of the input from the first layer. The second layer also calculates the final output [4,5].

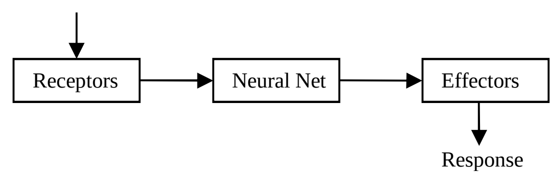

Figure 3: Generalized operation of a feed forward neural network system [1].

The implemented ANN consists of the stimuli/inputs to the receptors which process the input. The input to the ANN consists of 5 values:

- The battery capacity (Ah)
- The voltage/current over three time steps (t_1, t_2 and t_3)
- Operational temperature

The output is assigned a value between 0 and 1 and represents 0% and 100% effective capacity, respectively, of the SOC at that time.

B. ANN Revised Implementation

The data collected from testing batteries [1] and MATLAB simulated math model data are being used to train the ANN for various discharge current and temperature conditions. As shown in Figure 4, the ANN is a Tansig/Linear Neural Network (NN), which consists of 5 inputs, 14 hidden neurons and 1 output. The voltage, current and temperature data was processed into 5 different time-varying features that hold a strong relationship with the SOC [3]:

- Ampere-hour (Ah) discharged

- Time average current voltage and temperature
- Cumulative average of duty cycle.

The data used has been modeled using a constant load with five degree increments from -40°C to 80°C [3]. Figure 4 shows the overview of the feed forward network.

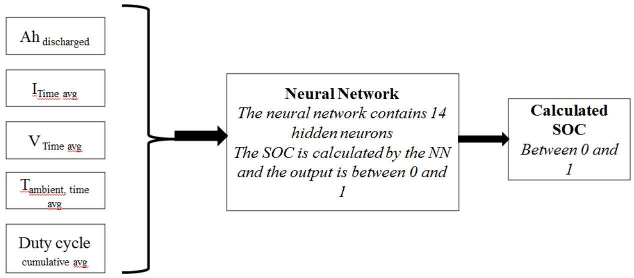

Figure 4: Feed forward ANN [3]

For each set of data at specified conditions, the training process was performed by using 60% of the data to train the network, 20% to validate the training, and 20% to test the ANN. The ANN has been tested using MATLAB.

Figure 5 shows the evaluation of the SOC algorithm with respect to the training data. In this case, the SOC has been trained with 60% of the data available for certain input conditions and then tested for 20% of that data [3]. As indicated below, the estimated and the true SOC values are nearly identical.

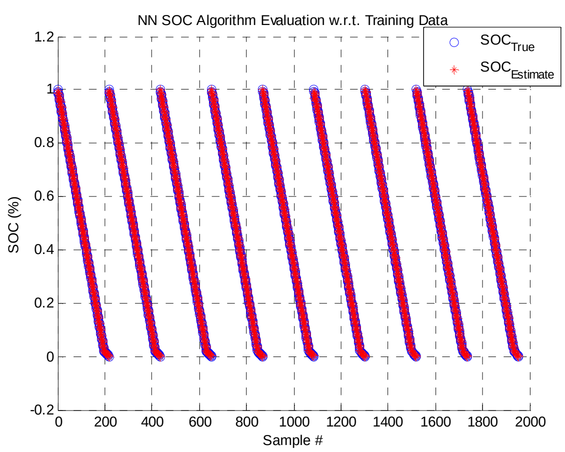

Figure 5: NN SOC Algorithm Evaluation for Training Data [3]

When calculating the percent error from Figure 5, the value was less than 1%.

The ANN has also been programmed onto the MSP430 and has been tested on the SOCI design as well by being a part of the system.

For the SOCI, the ANN was trained with temperatures from 24°C to 80°C [1]. The extreme cold temperatures were excluded in this case.

SOCI PERFORMANCE

The performance of the SOCI has improved over several versions. Contributing factors here are improvements in the hardware design, and increases in the accuracy of both the control software and the evaluating software.

C. Size

As shown in the figure below, the size of the board has been reduced significantly. The width of the SOCI has been brought down from 2.5" to 2.0". The horizontal white line on Version 5 indicates the space above which the circuit for the SOCI resides.

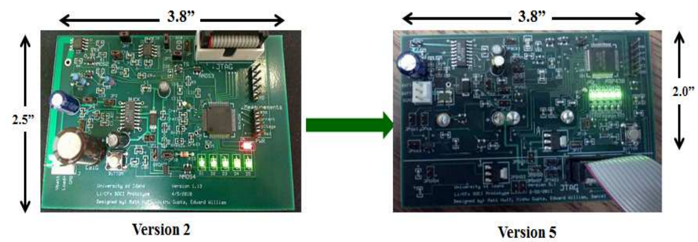

Figure 6: Sizes of Versions 2 and 5 [4,2].

D. Current Consumption

Table 2 provides an overview of the current consumption of the SOCI in various stages of operation, over different versions of the board. This is the current that the SOCI consumes from the LiCFx battery in different modes of operation [5].

Table 2: Comparison of current consumption of the SOCI board in different versions [1]

Mode	Requirement	Version 2	Versions 3 /4	Version 5
Sleep mode	$I_{SOCI} \leq 50\mu A$	2.52mA	52.0µA	50.1µA
Storage mode	$I_{SOCI} \leq 20\mu A$	2.52mA	52.0µA	50.1µA
ON mode	Not specified	34.98mA	11mA	5.1mA

Overall current consumption has decreased and, in all but one case, the set requirements are met.

E. Component Count

To help reduce the size, designs and number of components have been modified. Table 3 provides an overview of these changes.

Table 3: Component comparison [1]

Component	Version 2 board	Version 3 /4 board	Version 5 board
MSP430	YES	YES	YES
Buck Converter	YES	YES	YES
Boost Converter	YES	NO	NO
Current Sensor	YES	YES (modified)	YES (modified)
Voltage Sensor	YES	YES	YES
Temperature Sensor	YES	YES	YES
LED Display	YES	YES (modified)	YES (modified)
User Button	YES	YES	YES
SMBus	NO	NO	YES
3.3V Coin Cells	NO	YES	YES

F. Cost Analysis

Table 4 provides a cost comparison of the different versions. The SOCI design has significantly cut down on the total price of the board.

Table 4: Cost Analysis of the Different Versions

	Version 3 /4		Version 5	
	Initial Cost/Unit	**Bulk Cost/ Unit**	**Initial Cost/Unit**	**Bulk Cost/Unit**
Total Price (minus board)	$63.58	$26.94	$49.53	$23.96
Total Price	$100.82	$34.54	$85.48	**$31.56**

G. Accuracy

For the SOCI, accuracy is the most important feature. With the use of traditional methods and the ANN, the accuracy of the SOCI has increased. Table 5 provides the Accuracy Error of the sensors and the ANN.

Table 5: Accuracy Error [2,4,5]

	Version 2	**Version 5 board**
Voltage Sensor	<1.5%	<0.5%
Current Sensor	<1.5%	<0.5%
ANN accuracy	2%	<1.2%

The temperature sensor accuracy is not shown above, as it was unchanged.

CONCLUSION

This paper presented an overview of the use of Artificial Neural Networks to determine the SOC of a high-performance, flat-discharge-curve LiCFx battery. It also presented test results over multiple prototypes of the board. By utilizing the ANN, along with improved hardware and software, the overall accuracy of the board ranges from 96% - 98%. The accuracy error has been reduced to less than 1% in the final version (Version 5) of the board. The sensor accuracies have been brought under 0.05% for the current and the voltage sensors.

The ANN also provides an extra feature of making this SOCI trainable for other battery chemistries. As observed from the data, using the ANN technology on the SOCI board, the performance and the accuracy of the design have improved across several parameters such as cost, current consumption and the overall space used by the design.

Future work needs to be conducted to further improve the performance and utility of the SOCI board.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Clint Justin Govar for sponsoring this research under US MARCOR contract number M67854-08-C-653.

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