The Efficiency Measuring Apparatus for the Design of Li-Ion Batteries Equalizers

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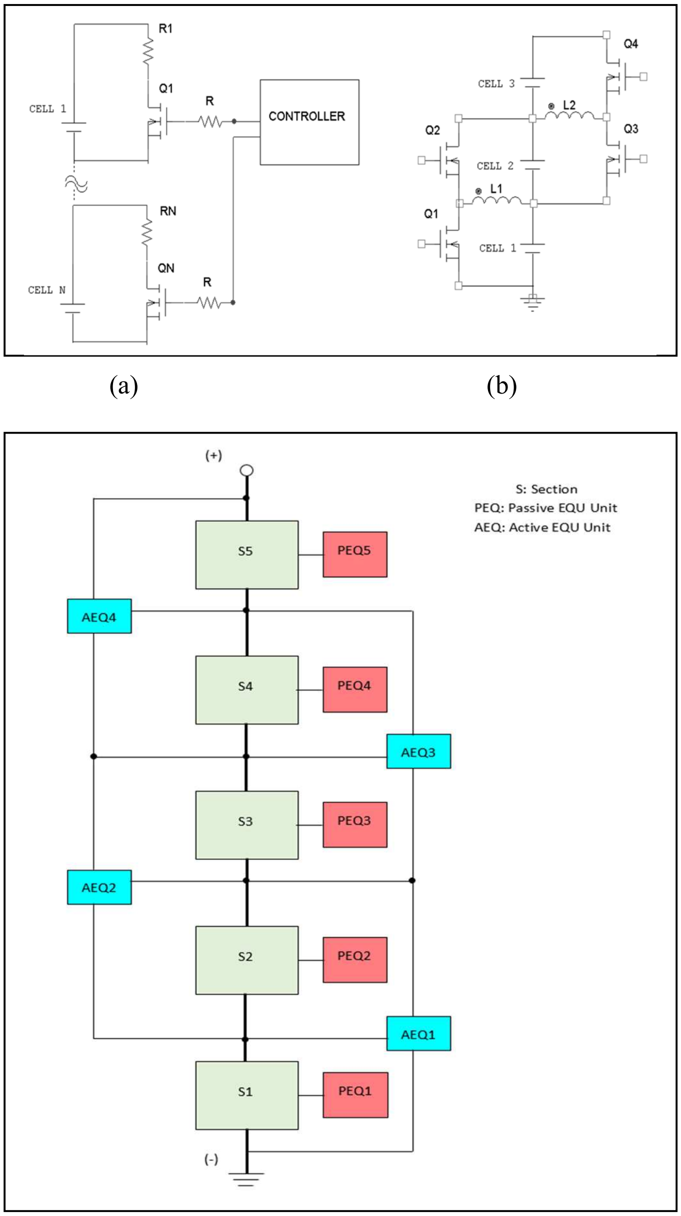
***Abstract*— Lithium ion batteries require an active equalizer (AEQ) or a Bilevel equalizer (BEQ) to transfer charges between the series connected cells or sections of cells. This research developed a suite of tools that are adequate for the design of BEQ and inductor based AEQs. The AEQ Inductor tool, the Efficiency Measuring Apparatus, and the EQU Design App were tested and validated against physical experimentation. The accuracy of these design tool proved to be higher than 98% compared to experimental results.**

Keywords—Efficiency, equalizer, lithium ion batteries, battery management system, design tool, inductor design, battery performance simulation, BMS, BESS, energy storage, cell balancing

I. INTRODUCTION

Most battery energy storage systems (BESSs) employ lithium-ion batteries because of their high energy density, good cycling life, superior power density and no memory effect. These batteries typically include several battery cells electrically coupled in series to provide the power and energy requirements. As a result of many factors, such as cell self-discharge rate, internal cell resistance, electrical connections, battery aging, etc., the state-of-charge of the cells in a battery may drift apart during operation of the battery over time. A battery management system (BMS) usually includes an electronic equalizer (EQU) to balance the cell voltages.

Current BMSs employ either a passive EQU or an active EQU, but not both. There are three types of equalizers: passive equalizers (PEQ), active equalizers (AEQ), and Bilevel Equalizers (BEQ). PEQs consist of a resistor in parallel with a cell as shown in Fig 1a.PEQ can only dissipate charges, which generates heat. As a result PEQ have a poor performance but they are inexpensive. The AEQ unit consists mainly of an inductor and two transistors as shown in Fig.1b. AEQs have a high performance but they are expensive costing 10 times more than PEQs. BEQs, which consist of both an active EQU and a passive EQU, have been proposed that balance the cell voltages at two different levels and provide high performance close to an active EQU, but at a low cost like a passive EQU in [1-6]. The BEQ divides the Li-ion battery stack into groups of cells that we call sections. Each section can have 1-14cells. Within the BEQ, PEQ units equalize the cell voltage while the AEQs units equalize the section voltage.



(a) (b)

(c)

Figure 1 (a) Simplified passive equalizer (b) simplest active equalizer (c) BEQ for battery with 5 sections

Fig.1c shows a block diagram for a BEQ system with 5 sections. Local units contain the controls and power components for the PEQs and AEQs for up to 12 cells. This includes an LTC6804 to measure the cell voltages and to control the PEQs and AEQs. Other electronic circuits including FET drivers also control the AEQs.

However, in order to manufacture and commercialize a BEQ, there is a need to develop a suite of design aid tools to systematically design the BEQ. Different tools were developed: the AEQ inductor design tool, the efficiency measuring apparatus (EMA), and the EQU Design App [1]. Although they were first developed to design the BEQ, these tools proved to be adequate for designing AEQs as well. The novelty of this research resides mainly in presenting a suite of tools that can be used to design both AEQs and BEQs and predict the performance of the battery stack under different equalizations. This work is protected under U.S. patent application 63/167,471 (pending) [7]. This paper describes the challenges, solutions, and experimental result in developing these design tools for Li-ion battery equalizers.

II. CHALLENGES

All controls for Li-ion applications require very high reliability and are cost sensitive. This creates the following challenges as to how the BEQ should be implemented:

1. The BEQ section can contain 1 cell, 4 cells, 6 cells, 12 cells or 14 cells. The question is how to evaluate the charge transfer efficiency for each of these. What design elements can affect the efficiency? There needs to be a way to test various design elements so that we can predict the BEQ performance.

2. The AEQ inductors serve as energy storage and affect the charge transfer efficiency. The inductors can be bulky, expensive and generate heat. Smaller inductors can be used, but they saturate at a lower current and would limit the equalization current, so there is a tradeoff between size, cost and efficiency. Factors that affect the inductor design are the inductance, magnetic force, and flux density.

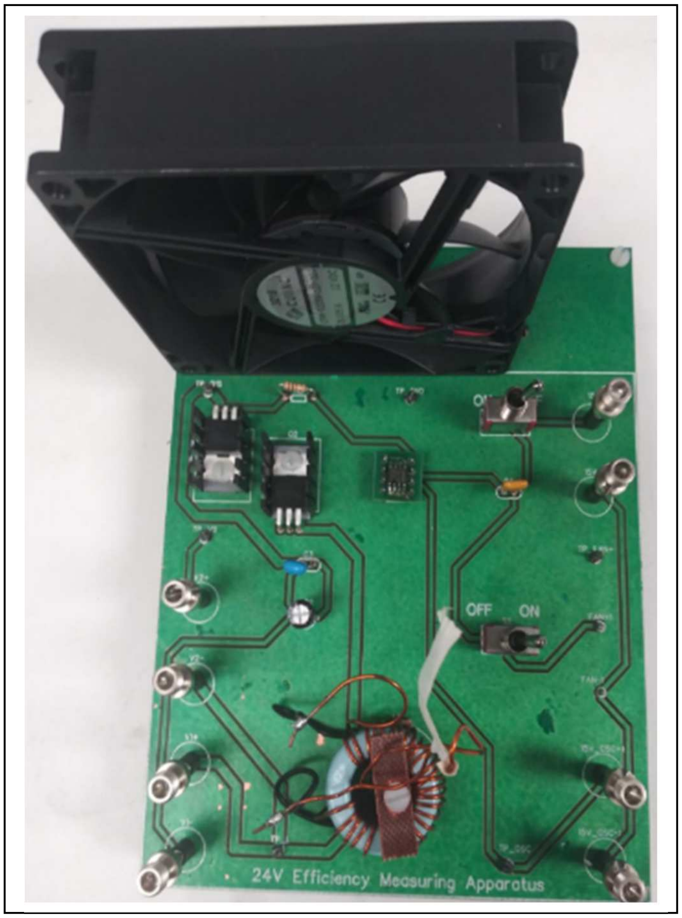
3. How to determine the size of the PEQ and AEQ currents? Higher currents provide correction for a higher level of cell imbalance, but at higher expense. Higher PEQ currents also mean higher heating losses. Factors that determine this are cell capacity, maximum discharge current, and level of capacity imbalance among the cells. This needs to be quantified to be able to determine a design specification.

4. Another question is how to model a battery stack and the BEQ performance so that all the cells reach discharge at the same time. This software for designing the BEQ is based on cell capacity, discharge current, section voltage, and level of capacity imbalance between the cells. The software will formulate the design criteria and specifications for the BEQ.

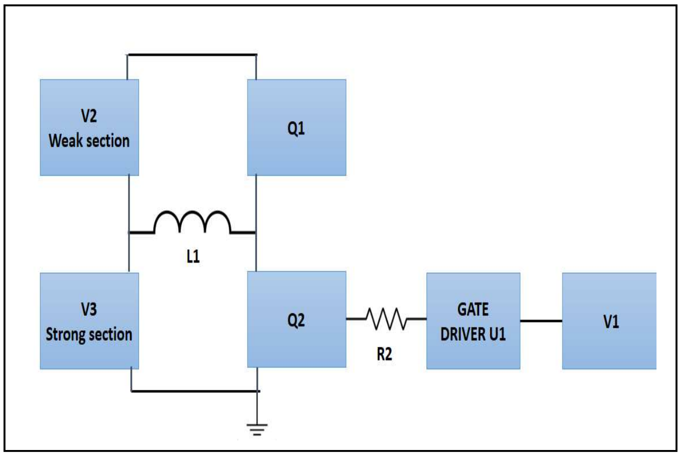
The next section describes the solutions that were developed to meet these challenges.

III. SOLUTIONS

1. **The Efficiency Measuring Apparatus (EMA)** which consists of an AEQ unit was designed and implemented to solve (challenge 1) [1]. The EMA measures the efficiency of the AEQ unit. First, an EMA for a BEQ section with up to 6 cells was designed and built as shown in Fig2(a) and (b). Then, another EMA for a 12 cell section was also assembled.



(a)



(b)

Figure 2. (**a**) 24V Efficiency Measuring Apparatus (EMA) implemented on a printed circuit board. (**b**) 24V Efficiency Measuring Apparatus bloc diagram

Per Fig.2 (b), V1 represents the DC power supply for the EMA, while V2 represents the low-capacity section, and V3 represents the high-capacity section. The AEQ power components consist of transistors Q1 and Q2 which are controlled by a PWM signal, and the inductor, L1. Q2 takes charge away from the high-capacity section, and the body diode in Q1 charges the low-capacity section. When one is ON the other is OFF. For safety reasons, they are not ON at the same time. The oscillator provides the pulse width modulation (PWM) signal that is needed to control the switching. The gate driver, U1, provides the drive signal to transistor Q2. Resistor R2 is needed to dampen a very high frequency oscillation at Q2 turn on.

The EMA AEQ unit with a 2 core toroidal inductor rated for 176uH and 125µ permeability was tested to measure the efficiency at various section voltages. Table 1 shows a summary of the efficiency at the different voltages. For example, the efficiency of a 14.4V section, with 2.5Adc current, I1, is about 76% at 12,690Hz.

I1 is the dc input current that flows into the inductor. While I2 is the dc output current that flows from the inductor.

2. **The AEQ Inductor Design Tool** was developed to design the inductors for the BEQ . There is a tradeoff between size, cost and efficiency of the inductors (challenge 2). The inductor stores energy during equalization and is a main factor that determines the energy transfer efficiency from one section to the next. If the inductor generates too much loss, then the transfer efficiency decreases. Therefore, to maximize the transfer efficiency, the inductor must be designed correctly. In addition, various designs must be compared prior to selecting an inductor. Table 2 shows various inductor designs and their respective efficiencies. The efficiencies were calculated using the AEQ Inductor tool. Then the AEQ units were physically built and their efficiency was measured using the 24V and 48V Efficiency Measuring Apparatus. Table 2 results show that the AEQ Inductor Tool has an accuracy ranging between 96% and 99.99%. In fact, in most cases, the accuracy is over 99% as can be seen.

TABLE I. EQUALIZER EFFICIENCY FOR 1, 4, AND 6 CELL SECTIONS.

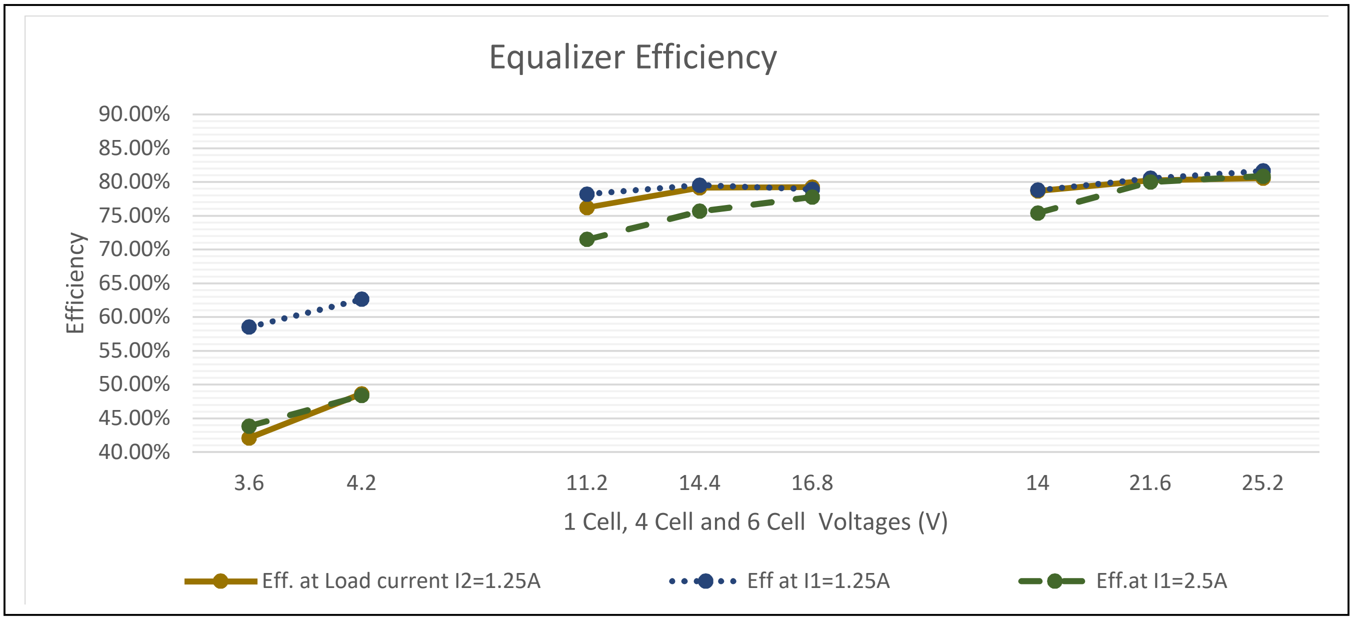


TABLE II. EQUALIZER EFFICIENCY CALCULATED BY THE AEQ INDUCTOR DESIGN TOOL ET MEASURED BY THE EMA

	Inductor Size (uH)	Inductor core#	Inductor winding size (AWG)	Freq. (Hz)	I peak (A)	Vin (V)	Measured Efficiency	Calculated Efficiency
48V EMA	32.4	MP-106026-2	22	77096	9	48	83.11%	84.01%
	31.1	MP-106026-2	20	76760	9.2	48	84.35%	84.75%
	32.8	MP-106026-2	18	76743	9	48	85.78%	85.21%
24V EMA	54.4	MP-106026-2	22	24456	10.9	24	82.94%	82.93%
	54	MP-106026-2	20	23704	10.9	24	83.67%	84.99%
	54.5	MP-106026-2	18	23704	10.9	24	84.4%	86.29%
	61.1	MP-106026-2	22	12667	9.9	14.4	77.17%	78.1%
	62.2	MP-106026-2	20	12531	9.9	14.4	79.6%	81.62%
	62.4	MP-106026-2	18	12531	9.9	14.4	80.4%	83.05%

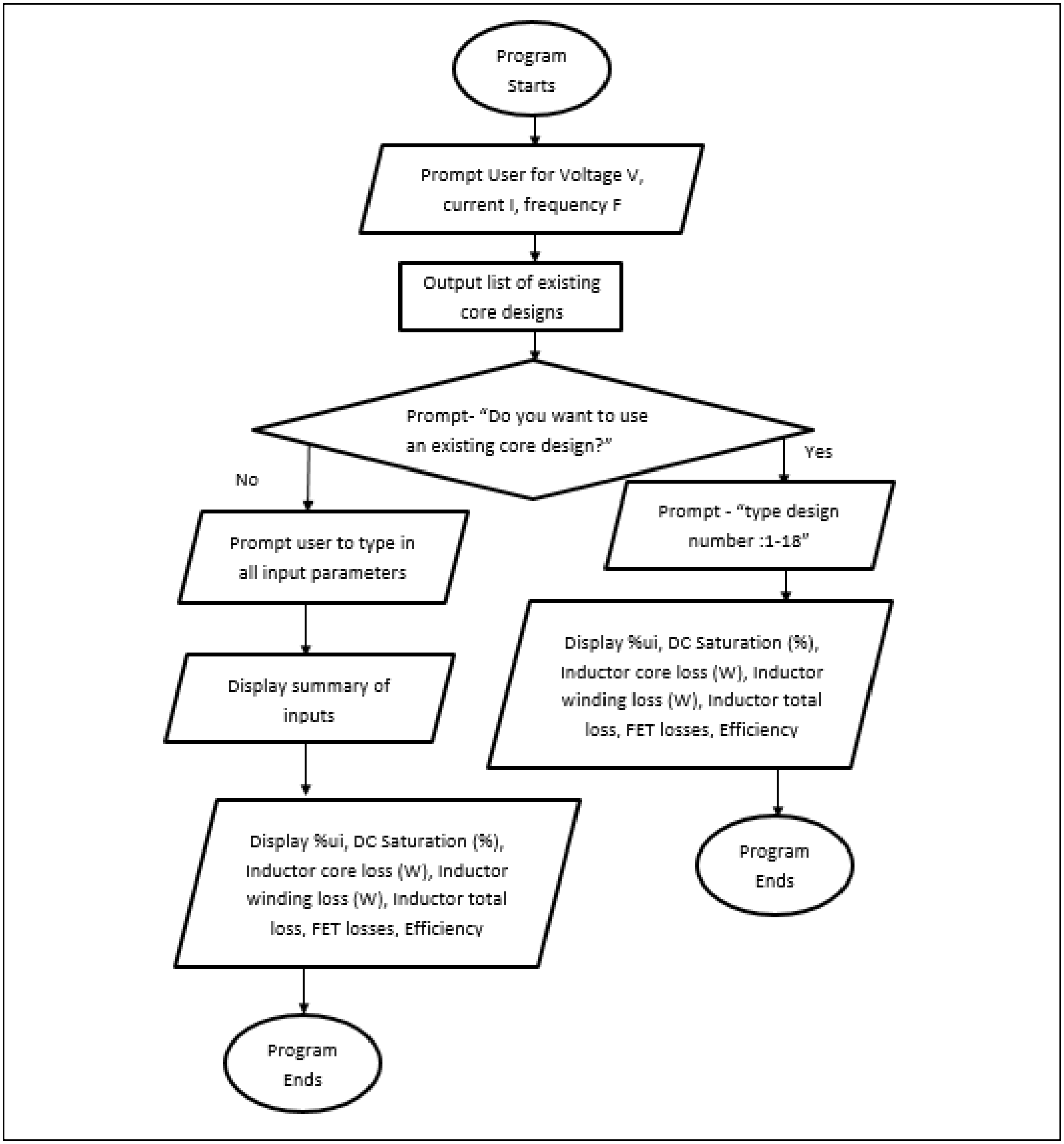


Figure 3. (**a**) Flowchart for the AEQ Inductor Design Tool.

The AEQ inductor Design Tool was first implemented in Microsoft Excel and then it was implemented in Python. Fig.3 shows the algorithm for the AEQ inductor design tool. The AEQ Inductor Design Tool asks the user to input the system voltage, peak current, and frequency. Then, it computes the inductor losses, the FET losses and the overall efficiency.

3. **The Equalizer (EQU) Design App** was developed in Matlab and Python to determine the equalization current, the design criteria for the BEQ, and to simulate a battery pack under equalization (challenges 3 and 4). The EQU Design App basically predicts the performance of a battery stack under purely active equalization or bilevel equalization. It also simulates a battery stack whose cells have different level of imbalance. The battery stack contains M cells connected in series. The BEQ divides the stack into sections of cells. Each section can contain either 4, 6, 12 or 14 cells typically.

Figure 4. Flowchart for the Equalizer Design App

The battery stack will have N sections given by (3.0) where N is the number of sections.

$$N = \frac{Total\ number\ of\ cells\ in\ the\ stack}{Number\ of\ cells\ in\ the\ section} \qquad (3.0)$$

The convention is that the capacity of a section is the capacity of the weakest cell within that section. The mathematical model of the Bilevel equalizer in matrix form:

$$\begin{bmatrix} n & 0 & 0 & 0 & Ah1 \\ -1 & n & 0 & 0 & Ah2 \\ 0 & -1 & n & 0 & Ah3 \\ 0 & 0 & -1 & n & Ah4 \\ 0 & 0 & 0 & -1 & Ah5 \end{bmatrix} . \begin{bmatrix} I1 \\ I2 \\ I3 \\ I4 \\ P \end{bmatrix} = \begin{bmatrix} Id \\ Id \\ Id \\ Id \\ Id \end{bmatrix} \qquad (3.1)$$

Where Ahi = rated Ah discharge capacity of section i (2 to N), ampere-hours ; Id = discharge current, amperes ; P = 1/discharge time, hours ; n = efficiency of each AEQ unit, 0 to 1.00.

The flowchart for the EQU Design App is shown in Fig.4. Note that the efficiency n was measured with the Efficiency Measuring Apparatus.

IV. EXPERIMENTAL RESULTS

The following methodology was used for experimentation. First, the AEQ Inductor Design tool was used to design the AEQ unit. Then, the design was implemented within the 24V Efficiency Measuring Apparatus which was built and setup in the lab as shown in Fig 5. Next, the measured efficiency from the EMA experimentations are entered into EQU Design App to predict the performance of the equalizers.

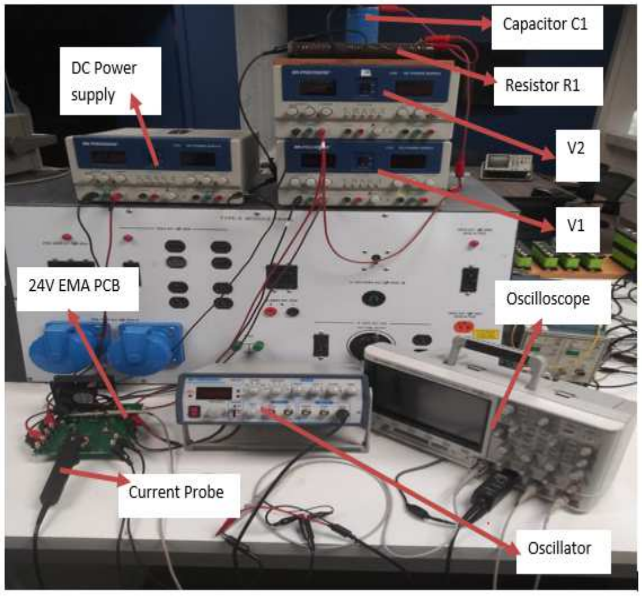


Figure 5. Lab setup for the 24V Efficiency Measuring Apparatus

The EQU Design App was first implemented in Matlab during the proof of concept. Since Matlab requires a license which is a limiting factor, in order to be more accessible and reach a broader audience, the EQU Design App was implemented with an open source software. Python was selected because it is an open software that is user friendly.

Some experiments conducted in previous research [1-6] would be simulated using the Python EQU Design App to validate the results. This section will compare the results from the Python EQU Design App to the Matlab EQU Design App and experimental results from the BEQ [8].

This example simulates the scenario of a battery stack that has a single weak cell scenario at the end of the stack. The battery stack contains 24 cells grouped into 6 sections of 4 cells with a section capacity of 22.03Ah. Since the equalization current flows between two sections, the number of equalization currents is equal to the number of sections minus one. Hence, in this case, a 6 section stack will have 5 equalization currents. The BESS has one weak cell in S1 with 19.25Ah capacity. The operating voltage for the 4 cells section is 14.8V, energy transfer efficiency is 76%, and the discharge current is 11.3A. The current flows from the high-capacity section to the low-capacity section. The BESS undergoes charge and discharge cycles.

The Python EQU Design App, Matlab EQU Design App, and the BEQ outputs are compared and shown below in Table 3 from [8].

The outputs from the Python EQU Design App and the Matlab EQU Design App show identical results. Note that both the Python and the Matlab EQU Design App are software simulation of the stack, whereas the BEQ experimental results are measured from the stack hardware. The first 5 rows of Table 2 show the equalization current into the corresponding section. According to the EQU Design App, for both the Matlab and Python versions, I1, the equalization current into S1, is predicted to be at least 1.37A. It is the highest equalization current in the stack. This is expected since S1 is the weakest section, and therefore the higher equalization current is needed to compensate for the larger imbalance in the stack. The discharge time is predicted to be 1.8764hrs. The Ah discharge is computed to be 21.2Ah which is about 96.25% of the rated Ah. For a BEQ, the stack discharge Ah is equal to the section average. For AEQs, the stack discharge Ah is equal to the cell average. For a PEQ, the stack discharge Ah is equal to the discharge Ah of the weakest section. Therefore the discharge Ah for the stack under

TABLE III. EQUALIZER DESIGN APP SIMULATIONS VS BEQ EXPERIMENTAL RESULTS.

Python EQU Design App	Matlab EQU Design App	BEQ Experimental Results [1][6]
1: EQU current is 1.37A 2: EQU current is 1.22A 3: EQU current is 1.03A 4: EQU current is 0.78A 5: EQU current is 0.44A Discharge time is 1.8764hrs Ah discharge is 21.2Ah Percent of rated AH is 96.25% Power loss is 17.18 W Energy loss is 32.25Wh Energy discharge is 1882.87Wh Discharge efficiency is 98.32%	1: EQU current is 1.37A 2: EQU current is 1.22A 3: EQU current is 1.03A 4: EQU current is 0.78A 5: EQU current is 0.44A Discharge time is 1.8764hrs Ah discharge is 21.2Ah Percent of rated AH is 96.25% Power loss is 17.19W Energy loss is 32.25Wh Energy discharge is 1882.87Wh Discharge efficiency is 98.32%	Discharge time is 1.91hrs Ah discharge is 21.57Ah Percent of rated AH is 97.91%

test would be 19.25Ah if it was balanced under passive equalization.

The BEQ has a discharge capacity of 21.57Ah which is very close to the expected value of 21.2Ah from the Python based tool [1,7]. Here, the Python based tool had an error of 1.71% in predicting the discharge capacity compared to the experimental results. The BEQ discharge time at 1.91hrs is very close to the Python tool projection of 1.8764hrs. The Python based tool had an error of 1.76% in predicting the discharge time in this scenario. The maximum possible EQU current at 2.5A in the BEQ is enough to provide the maximum expected EQU current of 1.37A to the battery sections. Therefore, the Python EQU Design App has an accuracy ranging between 98.24 % and 98.29% for predicting the performance of the Bilevel equalizer.

Based on these experimental results, the outputs from the Python EQU Design App are accurate and it is an adequate tool to predict the performance of the BEQ equalizers on a battery stack. Also, note that based on the mathematical model of the BEQ, each section represents a group of cells. For a pure inductor based AEQ, since each cell is connected to an AEQ unit, the inductor based AEQ is similar to a BEQ with 1cell-sections. Therefore, the EQU Design App can simulate the performance of the battery stack under inductor based active equalization and is adequate for inductor based AEQs.

CONCLUSION

Lithium ion batteries require an active equalizer (AEQ) or a Bilevel equalizer (BEQ) to transfer charges between the series connected cells or sections of cells. To design AEQs and BEQs, three tools were successfully developed.

First, the AEQ Inductor Design Tool was developed in order to design the inductor for the AEQ units that can be found in BEQs and inductor based AEQs.

Second, the Efficiency Measuring Apparatus (EMA) was developed to measure the efficiency of the charge transfer between series connected cells or sections of cells. This research developed two sets of hardware: the 24 EMA for sections with up to 6 cells, and the 48V EMA for section with up to 12 cells.

Third, the EQU Design App was developed to size the equalization currents and quantify the BEQ design specifications based on factors such as cell capacity, maximum discharge current and level of imbalance amongst the cells. The EQU Design App simulates the performance of the battery stack under BEQ equalization and can be used for inductor based AEQ.

The research methodology to obtain experimental results consisted of first using the AEQ Inductor Design Tool to design AEQs unit. Based on the outputs from the Inductor Design Tool, the inductor was built, and the switching components were selected as part of the AEQ units. Next the EMA, was used to test the AEQ units that were previously designed with the Inductor Design Tool. The EMA measured the charge transfer efficiency of the AEQ units under various parameters such as operating voltage, frequency, current etc. The efficiency computed by the AEQ Inductor Design Tool had an accuracy ranging from 96-99.99% compared to the measured efficiency from the EMA. These results show that the AEQ inductor Design Tool, the 24V and 48V the Efficiency Measuring Apparti were adequate tools for the design of Bilevel equalizer and inductor based active equalizers.

Thirdly, the EQU Design App was used to predict the performance of the battery stack under Bilevel equalization. The battery stack consisted of 23 cells with 22.03Ah and one weak cell with 19.25Ah discharge. This was done on purpose to simulate an imbalance.

As part of [1-6], the BEQ had been physically built with the AEQ unit that were designed using the AEQ Inductor Design Tool. A battery stack made up of 24 GAIA cells was assembled and placed in a thermal chamber for safety. The BESS was connected to the BEQ and submitted to various experimentation that can be found in [1-6]. These are the experimental results that were used to validate the design tools developed in this research. Experimental results showed that the Matlab and Python EQU Design App had an accuracy ranging between 98.24% and 98.29% for predicting discharge time, Ah discharge and percent of rated Ah. In conclusion, this research showed that the AEQ Inductor Design Tool, the Efficiency Measuring Apparatus, and the EQU Design App are adequate tools for designing Bilevel Equalizers and inductor based active equalizers.

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