A Selective Boost Equalizer for Series Connected NiMH Battery Packs

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***Abstract* - A unique selective equalization method has been developed to equalize nickel metal hydride (NiMH) battery packs. This technique uses a new selective boost equalizer that detects batteries either at a very low state of charge (SOC) or at an extremely high SOC. In this system a set of electromechanical relays is connected in a matrix to route boost current to the weaker batteries. A 32-bit microcontroller is used to control the relay switching, and the boost current is supplied by a separate boost charger. Once a weak battery is detected, it is scheduled for a specific boost time by a special "round robin" algorithm. The equalizer was tested on a pack of twelve series connected 12V 93 ampere hour NiMH batteries. Test results show that the equalizer was able to re-balance an artificially unbalanced pack, and the capacity was increased by 27% within six charge-discharge cycles. The number of cycles required to re-balance the pack was significantly reduced by using the "round robin" algorithm.**

***Index Terms* - Hybrid electric vehicle, Equalizer, Nickel metal hydride, Batteries.**

I. INTRODUCTION

Electric and hybrid electric vehicles (EVs and HEVs) use electrochemical secondary batteries which are connected in series packs to store energy for propulsion. The cell design, ambient temperature, and length of usage/storage are a few factors that affect the life or charge retention of these batteries [1]. This means that if there are certain subtle differences between the individual batteries, the batteries will not charge/discharge in a uniform manner. The result is that some units will be overcharged, some excessively discharged, and poor performance will result.

These charging and discharging imbalances pose an enormous problem for EVs and HEVs. These imbalances can be corrected by implementing a battery management system (BMS) which monitors certain parameters, such as the voltages and temperatures of individual batteries, and then takes corrective action whenever an imbalance arises [2]. For many types of batteries, the BMS simply monitors the voltage of each battery in the pack, and selects the lowest voltage battery for equalization. Several equalization methods described in [3-8] use this technique which is sometimes called selective equalization, and it works very well for batteries such as lead acid and lithium ion where there is a linear relationship between voltage and state of charge (SOC).

However, one of the more popular batteries used in today's HEVs is the nickel metal hydride (NiMH), and these batteries do not have a linear voltage-SOC relationship. The voltage vs. SOC characteristic for NiMH batteries is very different from lead acid or lithium ion. Fig.1 shows a typical voltage vs. depth of discharge curve for a 12V 100 ampere hour (Ah) Saft NiMH battery [9] where the voltage is fairly constant for most of the discharge cycle (this is called the voltage plateau). Because of this relatively flat voltage plateau, in practice it is impractical to detect a weak battery on the basis of its voltage except at very low or high SOC values. In a large series connected battery pack there actually could be several batteries with slightly lower voltages but higher SOC values than others with slightly higher voltages. This effect is aggravated by the fact that batteries with slightly higher impedance show a higher voltage during charging and a lower voltage during discharging. Therefore, it is very difficult to identify weaker batteries using the conventional selective equalization technique. A new equalizer is therefore required that detects weak batteries either at very low or extremely high SOC values and schedules them for a boost. Weak NiMH batteries can easily be detected at these SOC values because they tend to go out of voltage balance with respect to the other modules in the pack.

II. THE SELECTIVE BOOST EQUALIZER

The block diagram of the selective boost equalizer is shown in Fig.2. The equalizer was tested on twelve series

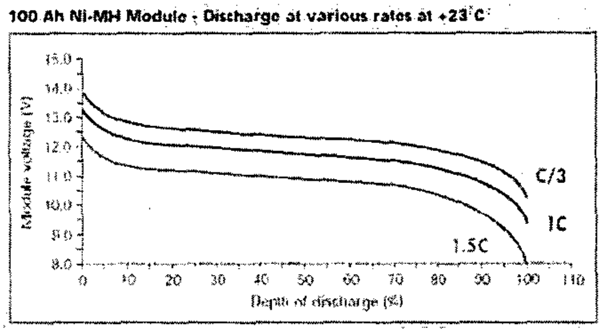

Fig.1. Typical discharge curve for NiMH batteries

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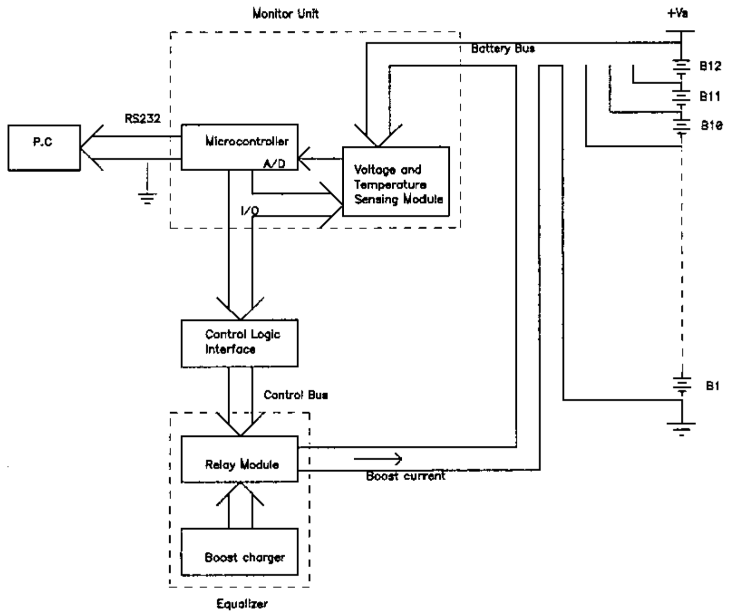


Fig.2. Selective boost equalizer system

connected 12V Saft NiMH batteries (B_1 - B_{12}) rated at 93 Ah. In this system, electromechanical relays and a separate boost charger were used to route the boost current to the weak batteries. A 32-bit Motorola M68376 microcontroller was used to implement the above tasks. Twelve isolation amplifiers (U_1 - U_{12}) were used to route the individual battery voltages to the microcontroller analog-to-digital converter (ADC) as shown in Fig.3. The microcontroller first detects the weak batteries, i.e., batteries that bring the discharge cycles to a premature end. When a weak battery is detected, a digital signal is sent from the microcontroller I/O port to a control logic interface circuit. This signal represents a number that indicates the battery selected to receive the next boost. The control logic interface circuit decodes the signal and turns on the required relays in a relay matrix module to route boost current from a separate charger to the selected battery.

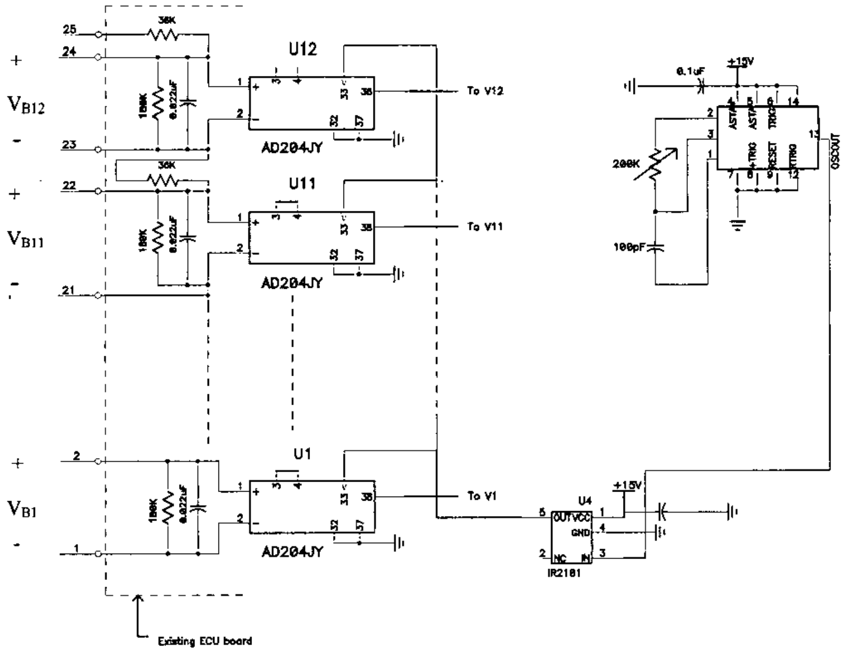
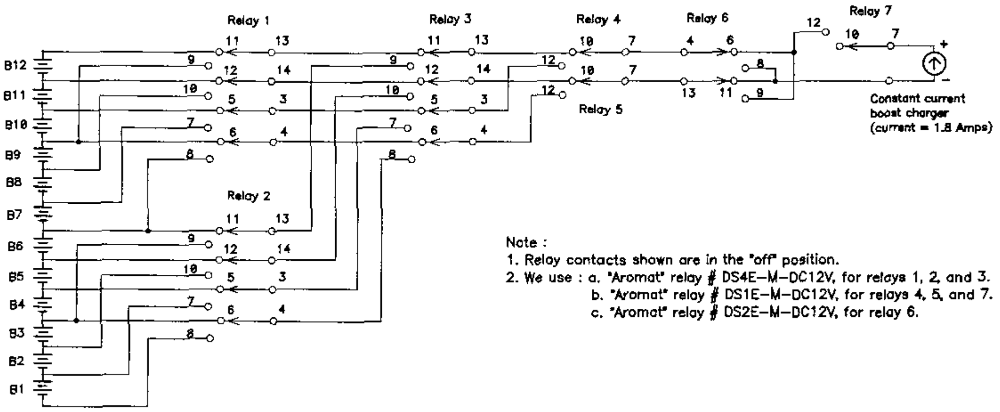


Fig.3. Isolation amplifier layout

The twelve battery voltages had to be scaled before inputting them to the microcontroller ADC since the maximum ADC voltage is only 5 V DC. A voltage divider circuit was used for this purpose to step down the voltage. The V_{B1}-V_{B12} outputs from the voltage divider were fed to the inputs of twelve isolation amplifiers (U_1 - U_{12}) as shown in Fig.3. Isolation amplifiers were used because all of the scaled voltages except V_{B1} are above ground and have to be shifted to the same reference level as the ADC. A sixteen channel multiplexer was used to route the isolated voltage signals V_1 - V_{12} to the microcontroller ADC.

Fig.4 shows the relay matrix module that comprises of seven relays, and Fig.5 shows the control logic interface module consisting of a set of FETs ($Q_1 - Q_7$), two latches, and eight NAND gates. PQA0-PQA5 (Port A of microcontroller) were used to output a 6-bit binary number that represents the weak battery that needs a boost. Table 1 shows the binary numbers for each of the twelve batteries and Table 2 shows the relays that turn ON when any of the twelve batteries is detected for a boost. For example, if battery B_7 is detected as the weak battery, the 6-bit data output from PQA0-PQA5 of the microcontroller corresponds to 100111_2 (in binary). This data is then latched onto the outputs of the two CD4042 latches causing FETs Q_1, Q_4, Q_5, and Q_7 to turn ON. Therefore, relays 1, 4, 5, and 7 turn ON, and boost current is



Note :
1. Relay contacts shown are in the "off" position.
2. We use : a. "Aromat" relay # DS4E-M-DC12V, for relays 1, 2, and 3.
b. "Aromat" relay # DS1E-M-DC12V, for relays 4, 5, and 7.
c. "Aromat" relay # DS2E-M-DC12V, for relay 6.

Fig.4. Relay matrix module

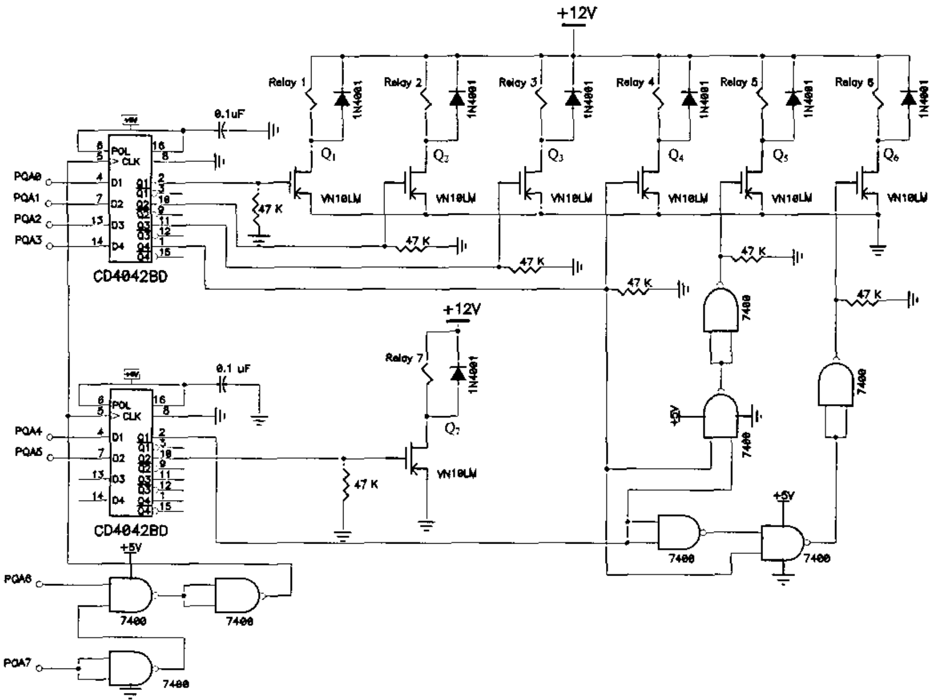


Fig.5. Control logic interface module

Table 1. Logic table for battery selection

Battery	PQA0	PQA1	PQA2	PQA3	PQA4	PQA5
B_{12}	0	0	0	0	0	1
B_{11}	0	0	0	1	0	1
B_{10}	0	0	0	1	1	1
B_9	1	0	0	0	0	1
B_8	1	0	0	1	0	1
B_7	1	0	0	1	1	1
B_6	0	0	1	0	0	1
B_5	0	0	1	1	0	1
B_4	0	0	1	1	1	1
B_3	0	1	1	0	0	1
B_2	0	1	1	1	0	1
B_1	0	1	1	1	1	1

Table 2. Logic table for relay selection

Battery	Relay 1	Relay 2	Relay 3	Relay 4	Relay 5	Relay 6	Relay 7
B_{12}	0	0	0	0	0	0	1
B_{11}	0	0	0	1	0	1	1
B_{10}	0	0	0	1	1	0	1
B_9	1	0	0	0	0	0	1
B_8	1	0	0	1	0	1	1
B_7	1	0	0	1	1	0	1
B_6	0	0	1	0	0	0	1
B_5	0	0	1	1	0	1	1
B_4	0	0	1	1	1	0	1
B_3	0	1	1	0	0	0	1
B_2	0	1	1	1	0	1	1
B_1	0	1	1	1	1	0	1

1 = Relay ON, 0 = Relay OFF

routed to B_7. Relays 1, 2, 3, 4, and 7 were driven by signals directly from PQA0, PQA1, PQA2, PQA3, and PQA5 respectively. However, relays 5 and 6 were controlled by a set of NAND gates in conjunction with microcontroller signals PQA3 and PQA4. This was done in order to perform the function of reversing the polarity for batteries B_2, B_5, B_8, and B_{11}, so that the positive terminals of these batteries are connected to the positive terminal of the boost charger whenever any one of these is selected for a boost.

Small sealed telecommunication relays were used to achieve high reliability and low cost. The new equalizer used a special algorithm described in [10] that routes boost current to the weaker batteries in a "round robin" fashion rather than giving each battery a complete boost. Thus, every weak battery gets some boost without excessive delays. This technique means that during the subsequent discharge cycles, more Ah can be taken out of the weaker batteries.

III. EXPERIMENTAL SYSTEM AND PROCEDURES

A block diagram of the system is shown in Fig.6. Separate wires were used for voltage sensing, temperature sensing, and boost equalizing. The voltage sensing lines and boost charging lines were connected to the batteries via 2 A DC fuses. Chilled water was circulated through the batteries during pack cycling using a 4.3 gal./min. chiller. The chiller was used to maintain the battery temperatures within the specified limits during cycling. A DC power supply was used for charging the pack and a variable resistive load was used for discharging. Charge cycles were carried out using a bulk charge of 29 A DC and a trickle charge of 4.7 A DC. The power supply output current and its ON/OFF operation were controlled by the microcontroller based on battery voltage and charge current measurements. The load was controlled manually during the discharge cycles to produce a discharge current of approximately 50 A DC for most of the discharge cycle. Towards the end, the load resistance was gradually increased until the discharge current decreased to about 15 A DC. This procedure was used in order to extract a slightly higher charge from the pack during the discharge cycles. The duration and amount of current allowed to flow through the pack during the charge and discharge cycles were based on the battery manufacturer's specifications.

The power supply current was controlled by an analog voltage during the charge cycles. A voltage, V_2, of 0 to 100 mV applied to the control terminals corresponded to an output current (I_o) of 0 to 50 A DC (Fig.7). V_2 was controlled by the microcontroller using a digital-to-analog converter (DAC0830) to produce the following relationship:

$$V_2 = -V_1 \text{ X } 100\ \Omega / (5\ \text{K}\Omega) - V_1/50 \qquad (1)$$

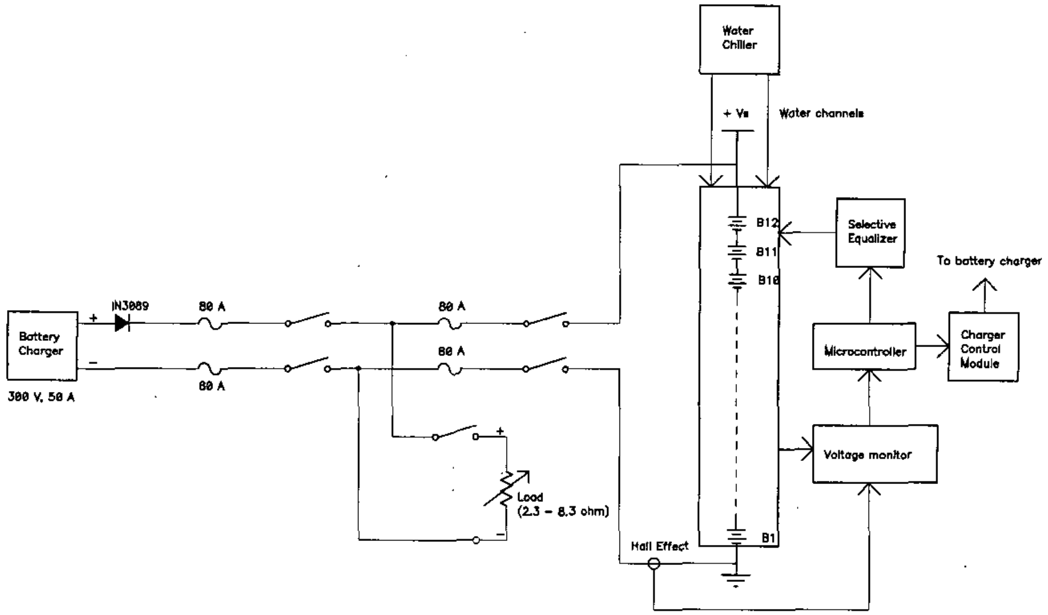


Fig.6. Experimental system

where: $\pm V_1 = \pm V_{REF}$ X ±digital code from microcontroller.

The ON/OFF control circuit for the DC power supply is shown in Fig.8.

IV. EXPERIMENTAL RESULTS

The initial set of tests made use of a relatively simple method wherein weak batteries were boosted individually for a specified period of time during charging and discharging. During these initial tests, if more than one weak battery was detected, the first battery was given a complete boost before attending to any of the others. These tests also indicated that the threshold value for detecting these weaker batteries during the discharge cycles was about 0.4V, i.e, weaker batteries could be identified when their voltages fell 0.4V below the average pack voltage [10].

As noted earlier, the 12V NiMH batteries used in these tests had a capacity rating of 93 Ah. About 10 % of the rated Ah, i.e., approximately 9 Ah was removed from one of the batteries after fully charging the pack. This was done to deliberately create an artificial unbalance in the pack so that the equalizing process could be effectively tested. The relays

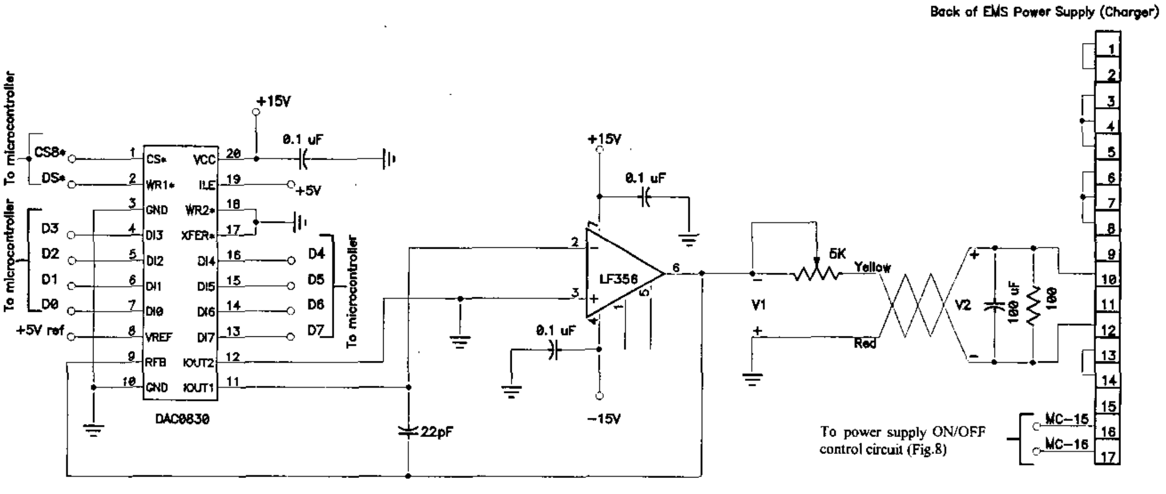


Fig.7. Power supply current control circuit

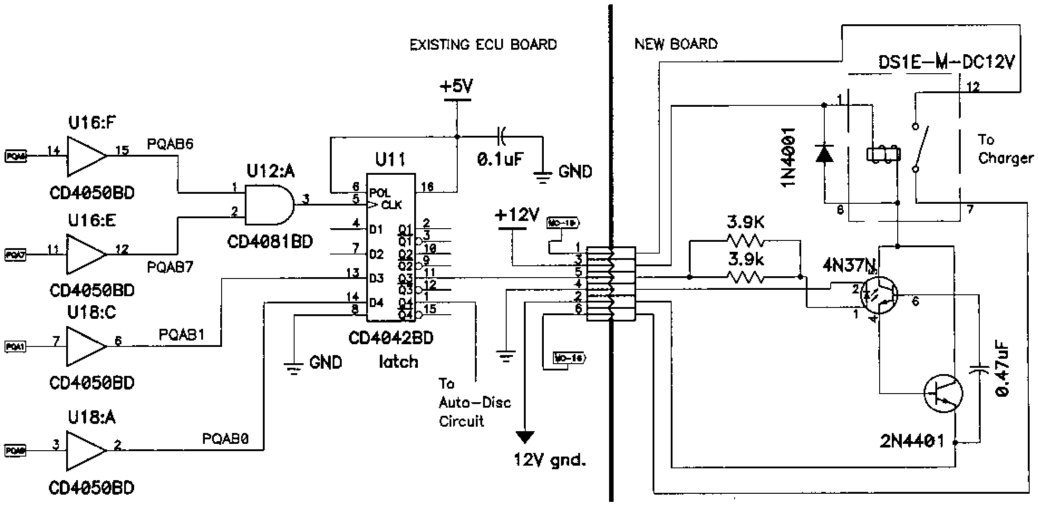


Fig.8. Power supply ON/OFF control circuit

used in the relay matrix module of the equalizer were 12V 1.8 A DC telecom type Aromat relays [11]. Therefore, the boost current was limited to 1.8 A DC, but other relays would allow higher current ratings. Each detected weak battery was scheduled for a boost time of about 5 hours to insure that the total Ah added to the weak battery equaled about 9 Ah. Actually, in practice the proper Ah of boost would be very difficult to determine because the optimum Ah boost should be only slightly greater than the Ah of the unbalance which, of course, is unknown. If the boost is much greater than the unbalance, significant energy loss will occur due to overcharging, and if it is too small, balance will not be achieved. In order to reduce this problem, later tests made use of a special "round robin" algorithm that boosted weak batteries in several smaller "doses" [10]. Overcharging was reduced by discontinuing the "doses" once the battery was no longer detected as a weak unit.

The initial test results revealed that the technique of providing a complete boost of 9 Ah to battery "x" before proceeding to battery "y" worked fairly well when only one or two batteries were scheduled for a boost, but further tests revealed that if three or more batteries are scheduled, the procedure is less effective. This is because the boost is not uniformly distributed among the defective batteries. This results in some of the batteries getting a complete boost before the commencement of the next discharge cycle, while the rest might not yet receive any boost. Fig.9 shows the results obtained where 9 Ah was purposely taken out from one battery (B_3) to create an artificial unbalance in the pack. As expected, battery B_3 was detected for a boost at the end of discharge cycle #1. During cycle #2, battery B_3 got a complete boost. Therefore, at the end of discharge cycle #2, B_3 was not detected to be the weakest battery. In fact two other batteries with slightly higher impedances, B_7 and B_8, were detected and were scheduled for a boost, and the Ah recorded at the end of discharge cycle #2 improved to 86.6. During the subsequent discharge cycle, i.e. #3, the Ah improved to 93.1 (SOC ≅ 100 %), but the microcontroller detected three weak batteries viz. B_7, B_9, and B_{10}. Battery B_7 was scheduled for a boost again because it did not receive a sufficient amount of boost during the previous cycle (discharge cycle #3). Although the pack SOC was approximately equal to 100 %, it was decided to observe the effect of these three weak batteries on the discharge Ah by continuing the pack cycling. The equalizer first started boosting B_7 during cycle #4. However, it failed to completely boost battery B_9 and B_{10} before the commencement of cycle #5. As a result, battery B_9 was detected for a boost again at the end of discharge cycle #4, and the capacity of the pack decreased to 87.6 Ah. With further cycling the capacity improved gradually from 87.6 Ah to 93.5 Ah (SOC ≅ 100 %) because in each of the subsequent cycles viz. #5, #6, #7, and #8, either battery B_7 or B_8 was detected for a boost, and it was boosted completely before the start of the following cycle.

The second set of tests made use of the "round robin" algorithm to boost the defective batteries. Fig.10 shows the results obtained in one such test wherein three batteries (B_5, B_9, and B_{10}) were purposely unbalanced (9 Ah was taken from each of them) in order to test the algorithm. During

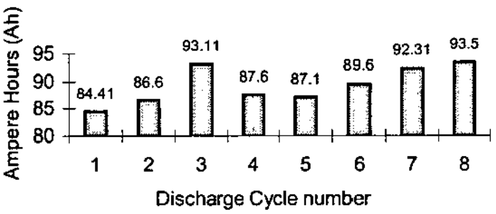


Fig.9. Equalization results without using the "round robin" algorithm

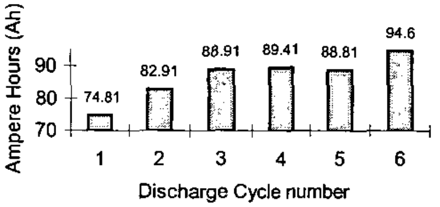


Fig.10. Equalization results using the "round robin" algorithm

discharge cycle #1, the algorithm detected the above three batteries and scheduled them for a boost. The boost current was set to 1.8 A DC and the total boost time for each detected battery was set to 5 hours so that the total Ah added to each battery equaled 9 Ah. Each weak battery was boosted in small "doses" of 54 minutes in a "round robin" fashion. The period of each dose was selected to be 54 minutes so that about 1.6 Ah (18 % of the total 9 Ah unbalance) was added during every dose. The pack capacity increased from 74.8 Ah to 94.6 Ah (slightly above the 100 % SOC rating) after six charge and discharge cycles as shown in Fig.10. The total number of cycles required for the artificially unbalanced pack to be re-balanced were thus significantly reduced by using the "round robin" technique. This occurred even though the test had three purposely unbalanced batteries, whereas the previous tests only had one.

V. CONCLUSIONS

The new selective equalizer proved to be very effective for equalizing the twelve series connected NiMH batteries. The technique used for equalization is a universal one and is not restricted to one particular type of battery. This is because the equalization principle does not follow the traditional method of picking the cell with lowest voltage for equalization, but instead looks for batteries that initiate the end of the charge and discharge cycles. Several tests were carried out in order to evaluate this equalizer. The traditional technique of boosting a weak battery completely before attending to another weak battery worked reasonably well, but the time required to equalize the pack was reduced even further by using a "round robin" technique. The optimum amount of boost current and time will differ from battery to battery, and this depends on a variety of factors such as the individual battery characteristics and SOC ratings.

The equalizer is compact and makes use of inexpensive components. Moreover, it can be broken down into modularized units located close to the batteries so that each unit serves a particular section of the battery pack. Since EVs and HEVs require several series connected batteries, these modularized versions [12] are probably the best choice for future implementation. The lifetime of relays used was rated at a minimum of 5×10^5 switching operations at a current of 2 A DC [11]. Based on the much lower number of expected switching operations, this indicates the equalizer should easily outlast the life of an HEV. The voltage sensing module in these tests used twelve isolation amplifiers for measuring individual battery voltages. The cost and size of the voltage sensing unit can be drastically reduced by using cheaper techniques such as a voltage transfer circuit [13] or an op amp transfer circuit [14] instead of these isolation amplifiers. The need for separate boost lines could be eliminated by locating the equalizer closer to the pack and also using the voltage sensing lines for boosting the batteries.

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