A New Charge-Discharge Equalization Technique for Series Connected Battery Cells

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Abstract

The proposed technique a) provides both charge and discharge equalization and supports battery operation even with damaged cells b) ensures a uniform battery cell voltage fall, thus protecting cells from reverse polarization, and c) maximizes the energy delivered by the battery. The operation has been verified both by simulation and by experimental results.

1. Introduction

There are a variety of applications where batteries are the primary option for electric energy storage. Electric road Vehicles (EV), Uninterruptible Power Supplies (UPS) and cordless electric power tools are examples of such typical applications. The conceptual behavior of batteries and the relation between charging and battery degradation is examined in [1]. Usually the degradation of a battery cell causes an increase in its internal resistance, but in some extreme cases, an internal short circuit may result. In both cases, the performance of the whole battery is affected. The necessity of charge equalization for maximizing battery life led to the development of several equalization schemes [1-4]. With most of these schemes, discharging equalization cannot be used and, consequently, the maximum power that a charge equalized battery can deliver is limited by the battery cell having the minimum capacity. If a battery cell becomes defective, the whole battery performance is affected.

Battery cells with alkaline electrolyte (nickel cadmium cells) are usually used in cordless electric power tools and must be deeply discharged before a new recharge cycle takes place in order to avoid dendrite growth inside the cells. In this case, it is necessary to get most of the charge stored in each cell, despite cell non-uniformity. Cell non-uniformity may cause any discharged cells to become reverse polarized, while the rest of the cells may be prevented from deep discharging. Similar phenomena of reverse polarization of certain cells may occur in lead-acid batteries, if it is attempted to discharge them below a certain level.

If no discharging equalization is used the following problems may exist:

- Less energy retrieval
- Deterioration of battery voltage characteristics
- Possible shortage of battery life.

The need of a simple technique that can be applied to homogeneous cell strings, regardless of the string chemistry or cell voltage and can provide both effective charge and discharging equalization led to the design of a simple converter which can effectively connect all the cells of a battery such that the voltage across each cell is approximately the same. To achieve this, an efficient DC/DC converter is applied around a multiwinding High Frequency transformer. The basic diagram of the proposed equalization technique is shown in Fig. 1. The main advantage of the proposed technique is that its implementation results in a relatively light and small size construction. Moreover, it is characterized by a flexible design, which can be easily adapted to various charge and discharging requirements.

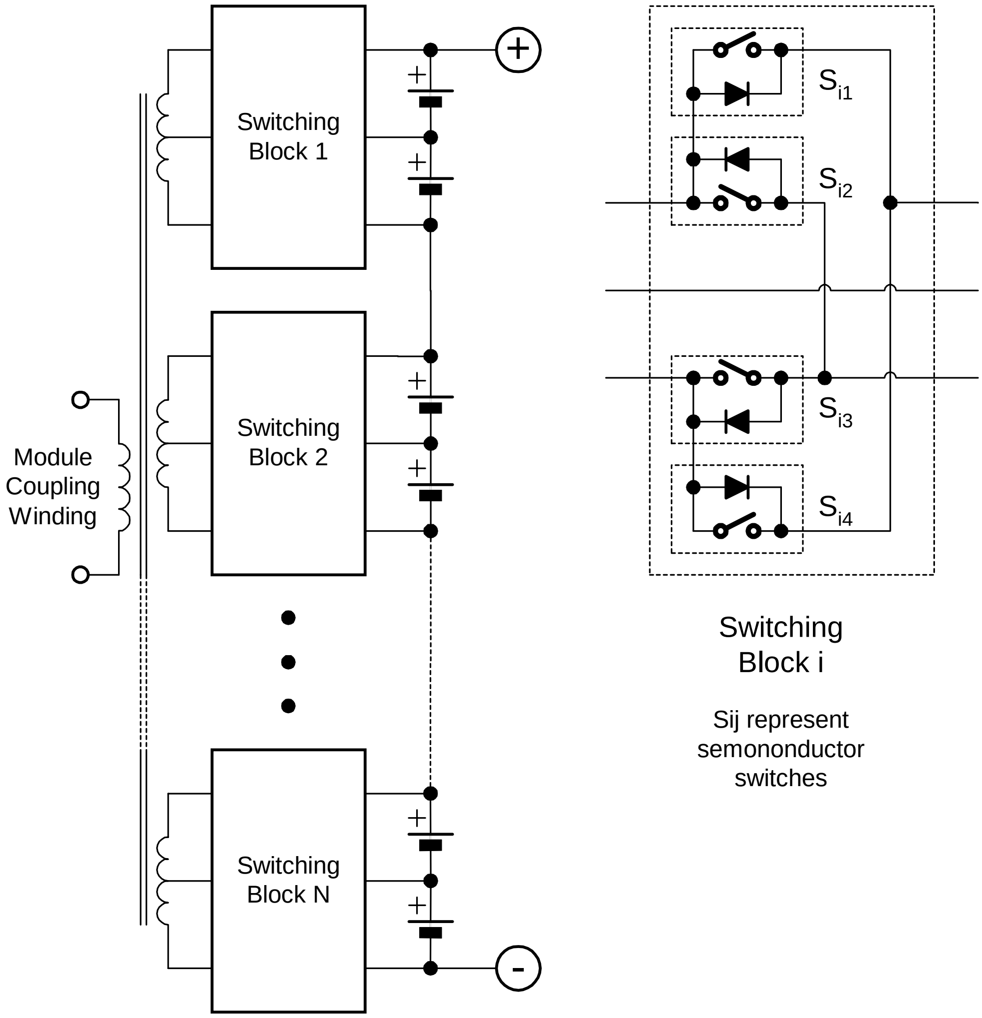

Fig. 1: The basic diagram of the proposed technique.

The principle of operation of the proposed method is given in section 2. The cooperation of the proposed technique with a Battery Management System (BMS) is discussed in section 3, while the simulation and experimental results are presented in sections 4 and 5, respectively.

2. Principle of Operation

As shown in Fig. 1, the proposed equalization technique is fully symmetric for an even number of N cells, utilizes a transformer having a number of center-tapped windings equal to N/2 and a module coupling winding. Each center-tapped winding is connected to two adjacent battery cells through four switch-diode pairs as shown in Fig. 1. The switches are turned on and off alternatively. Thus a full wave rectified, bi-directional, push-pull DC/DC converter is formed for each battery cell, which equalizes the battery cell voltages. It is noted that, if the ON-switch resistance is zero, there is no current through the diodes. However, current may flow through the diodes, if no bi-directional switches are used or if the switches have considerably high ON-resistance. The fully symmetrical operation of the transformer causes a voltage pulse to be induced in the module coupling winding, proportional to the cell voltage, so this winding can be used to couple additional transformers, This gives the flexibility to combine the circuit with other equalized battery systems by simply cascading them. When there is an odd number N of battery cells to be equalized with such a transformer, then the required transformer should have (N+1)/2 center-tapped windings.

Enhancement type n-channel power MOSFETs are used as switch-diode pairs, because they have a very low ON-state voltage drop. They feature the additional advantages that they are easily driven and that they usually include a diode in parallel with their parasitic diode. Such a MOSFET turns “ON’’ only with a positive pulse and can be turned “OFF’’ with a zero or negative voltage. All these three voltage levels can be produced by only one multiwinding transformer, which drives all MOSFET-switches shown in the circuit of Fig. 1. All MOSFETs stay in ‘OFF’ state with zero voltage at their gates. The switches S_{i1} and S_{i3} are driven to the ‘ON’ state with a positive voltage pulse and are driven to the “OFF’’ state with a negative pulse, which in sequence drives S_{i2} and S_{i4} to the ‘ON’ state. The use of the zero voltage level is explained in section 3 (Charging Operation). In cordless tools powered by rechargeable battery packs, where the weight is a significant parameter, the module-coupling transformer winding shown in Fig. 1 is not used. Thus, the rest of the circuit is used only for discharging equalization and the MOSFET switches can be driven ON/OFF simply by a second multiwinding transformer driven by a multivibrator powered from the tool turn-on switch.

To apply discharging equalization, the power semiconductor switches S_{i1}, S_{i3} and S_{i2}, S_{i4} are turning ‘ON’ and “OFF’’ alternatively. In this case, each cell is always connected to the one half of a center-tapped winding. Because all these windings are identical, the voltages at their terminals are equal and, consequently, all the cells discharge under the same voltage. In discharging equalization, no problems arise if battery cells discharge under the same voltage. Under this condition, all battery cells supply current to the load. This current depends mostly on the battery cell internal resistance, which increases rapidly as each battery cell reaches the knee of its discharging characteristic [5]. The equalization controls the current of each battery cell in such a way that all the cells discharge almost simultaneously. Thus, the battery voltage is maintained approximately constant until the battery discharging point is reached, because under this condition polarity reversal of any cell cannot occur. This permits deep discharging in alkaline electrolyte battery cells, thus avoiding dendrite growth.

Charge equalizers are usually based on the concept that cell voltages depend on battery chemistry, temperature and other related parameters, but the individual cell voltages have the same value, once they have reached the final state of charge [2]. The only obvious exception is the case of short-circuited cells for which charge equalizers use fuses that disconnect the respective charging paths through which these cells are equalized [3]. This approach assumes that a battery with a short-circuited cell can be usable, but this assumption needs further consideration. For example, if no discharging equalizer is used, such a cell may release toxic and flammable gases or increase its temperature above the safe levels during the battery discharging. If this is the case, it is better to stop battery charging and replace the defective cell. The proposed discharging equalization scheme has an advantage over existing discharge equalization topologies, because the string output voltage is smooth, without interruptions caused by the core stored energy transfer. In addition, existing discharge equalization schemes providing smooth output use a separate converter for each cell.

The charge-discharge equalization technique presented in this paper may use fuses, not necessarily the blow type but the current-controlled electromechanical type, which are connected in series with each battery cell and disconnect any short-circuited cells. This type of equalization system inherently regulates the voltage across the isolated battery cell and provides fault tolerance to the whole system.

The proposed technique applies two types of charge equalization. The first type operates the power semiconductor switches as in discharging equalization mode, thus giving low DC ripple. This type of equalization is used only if defective cells are present in the battery during the bulk battery charge. In this type of equalization the full rated transformer power can be used. In the case of charging a battery with normal cells, the bulk charging is performed without equalization. Then, when one of the cells reaches the threshold voltage, the second type of equalization is activated and invokes trickle charging applied through the module coupling transformer winding, with all the switches in the 'OFF' state. In this phase of equalization, only a part of the rated transformer power is used and therefore the shape of the current is not critical. Thus, for the trickle charging phase, the scheme proposed in [4] is used.

The proposed technique can form an integrated unit comprising the cells and the equalization circuitry. A number of such units can be connected together in a bigger modular system. If all transformers of the modular system are coupled by connecting their module coupling windings in parallel, then they behave as one transformer with a single coupling winding.

3. Integration with a Battery Management System (BMS)

From the previous system operation analysis arises that a BMS must be used to control the procedures described. It is important to note that permanently damaged cells have to be detected and be isolated from the battery, because they may be dissipative and can reduce the remaining load supply time and the overall battery performance. The proposed technique can be controlled by a BMS to provide discharging equalization during the whole discharging period, or only if a cell voltage reduces below a threshold level. During the charge period, the proposed system can operate under the following modes:

a. Charge all cells in series with all power semiconductor switches open,
b. charge all cells under the same voltage with non-controlled charging current,
c. charge all cells under the same voltage with controlled current from a ramp converter connected to the module coupling winding, a procedure used in the case of trickle charging.

The selection among these modes of operation, the detection of any defective cells and the decision for their isolation must be made by the BMS, taking into account the battery chemistry and its particular characteristics. The BMS must be capable of performing at least voltage, current and temperature measurement of each cell in order to provide fast and efficient charging, maximize battery life and improve load supply reliability.

The exact control algorithm depends on battery chemistry, desired charging time and the resulting efficiency of charge-discharge battery cycle energy. A BMS takes into account the capacity and most significant characteristics of each cell using a battery model. This makes possible the supply of maximum charging currents and the selection of the charging mode. Since such a system has a programmable operation, it is flexible and can easily be adapted to the specific battery operation conditions.

The additional cost that the proposed scheme induces to an existing BMS summarizes to: two MOSFETs per cell, a HF transformer per battery, a current transformer and an OpAmp per MOSFET and additional A/D ports on the BMS microprocessor. The BMS upgrading benefits are: a) charge equalization, b) discharge equalization and c) isolation of the defective cells or batteries without string operation interruption, which is very useful in some crucial situations, such as faraway signal repeaters and electric vehicles.

4. Simulation Results

In this section, the simulation results of the proposed equalization technique under charging and discharging conditions will be described. During charging, it is examined how the current is distributed through each cell, while during the discharging process, it is verified that the battery voltage does not fall below a threshold level. Fig. 2 shows the power switching circuit used in the proposed equalization technique in order to obtain simulation results and verify the theoretical analysis.

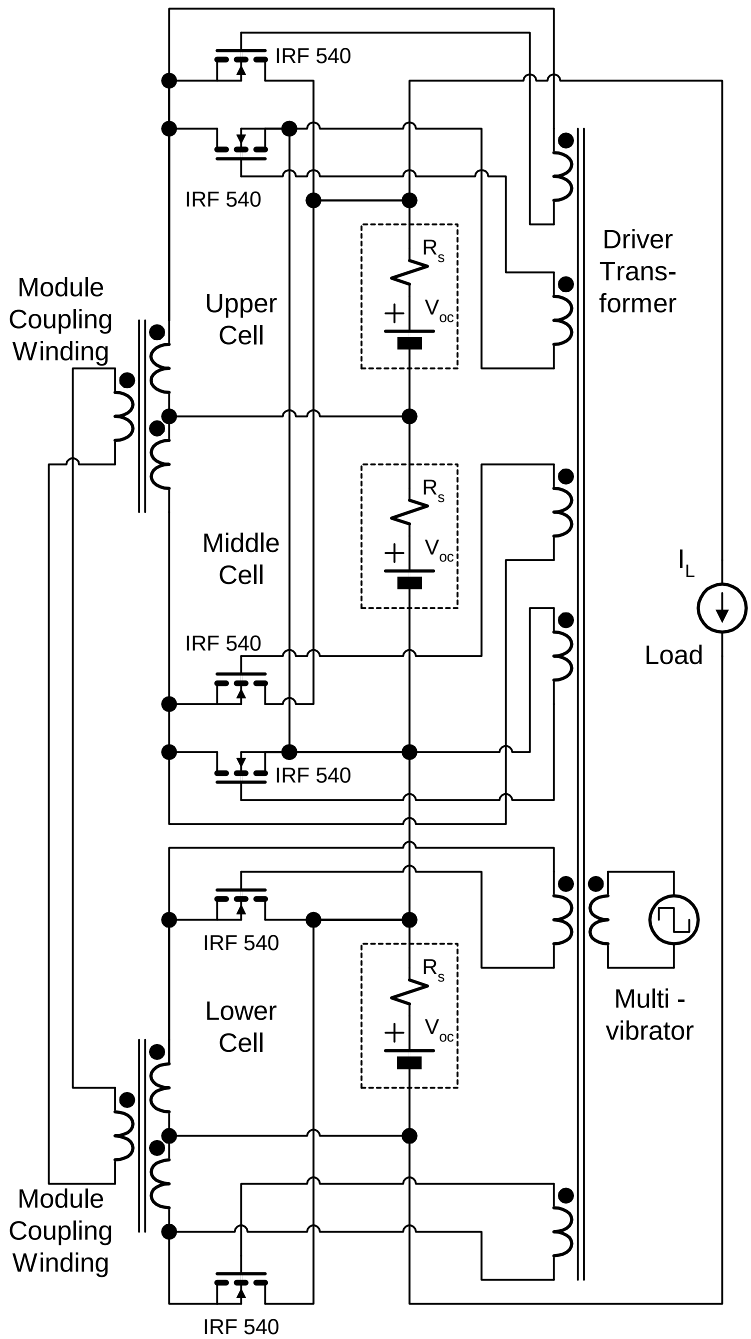

Fig. 2: The SPICE simulation circuit

As shown in Fig. 2, for simulation purposes, a simplified circuit for the equalization of three cells using two coupled transformers is considered. Each cell is represented with a voltage source and a resistor combination.

Several unknown parameters necessary for the simulation were determined by some experimental trial runs. Finally, a simulation model for the cell was derived, based on experimental charging and discharging characteristics of the available cells, because accurate generic simulation models are not available and cannot be elaborated. A cell model depends on many factors, such as cell type, age, temperature etc. that cannot be easily measured or simulated. The cell model used consists of a voltage source connected in series with a resistor. However, for improved accuracy, the resistance was considered to be an exponential function of the state-of-charge. Also, the voltage was described by a linear function for state-of-charge values between 10% to 90% and an exponential function for state-of-charge values less than 10%. This assumption is justified because the most interesting operating area for the proposed technique is towards the extreme states of charge. On the other hand, the simple linear model describes the cell operation fairly accurately in the usual operating area of state-of-charge (between 10% and 90%). The parameters of the exponential functions were roughly estimated using mathematical regression on the experimental results and then they were tuned in such a way that simulation and experimental results come as close as possible. The precision of the simulation circuit is limited mainly because the discharging characteristics of cells vary widely at high values of state-of-charge, which may cause an error in the value of the delivered charge. Thus, the initial state-of-charge of the cells needs to be tuned in order to obtain simulation behavior similar to the experimental one. The entire discharging and charging process was simulated and the results are shown in Fig. 3, 4 and 5.

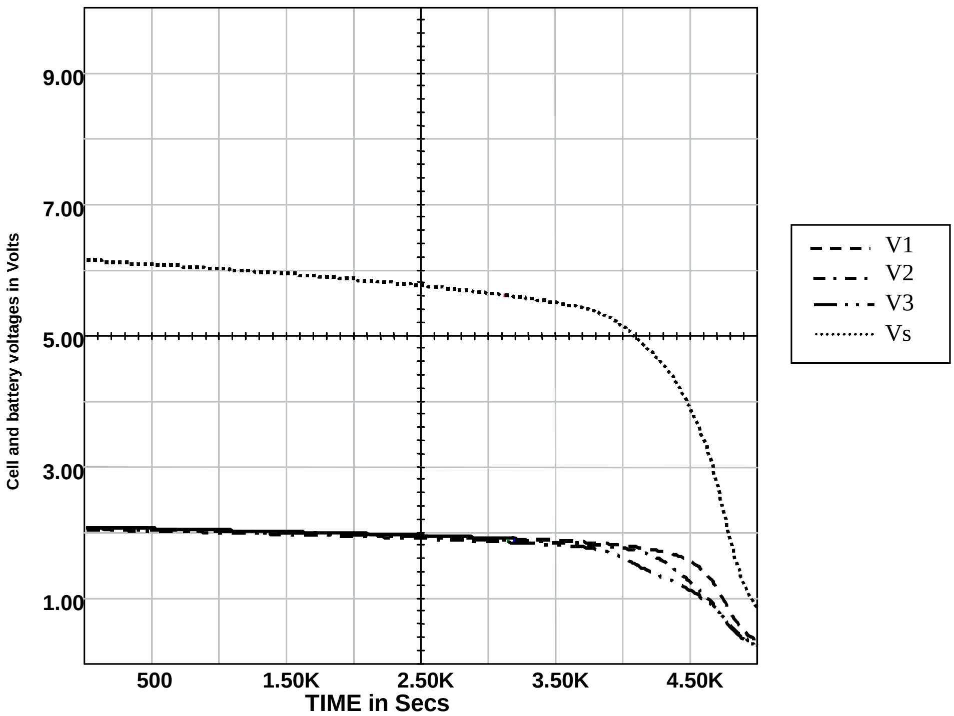

Fig. 3: Simulated discharging characteristics of three 6Ah cells with initial charge of 5.5 Ah (V1), 5 Ah (V2) and 4.5 Ah (V3). Vs is the total battery voltage.

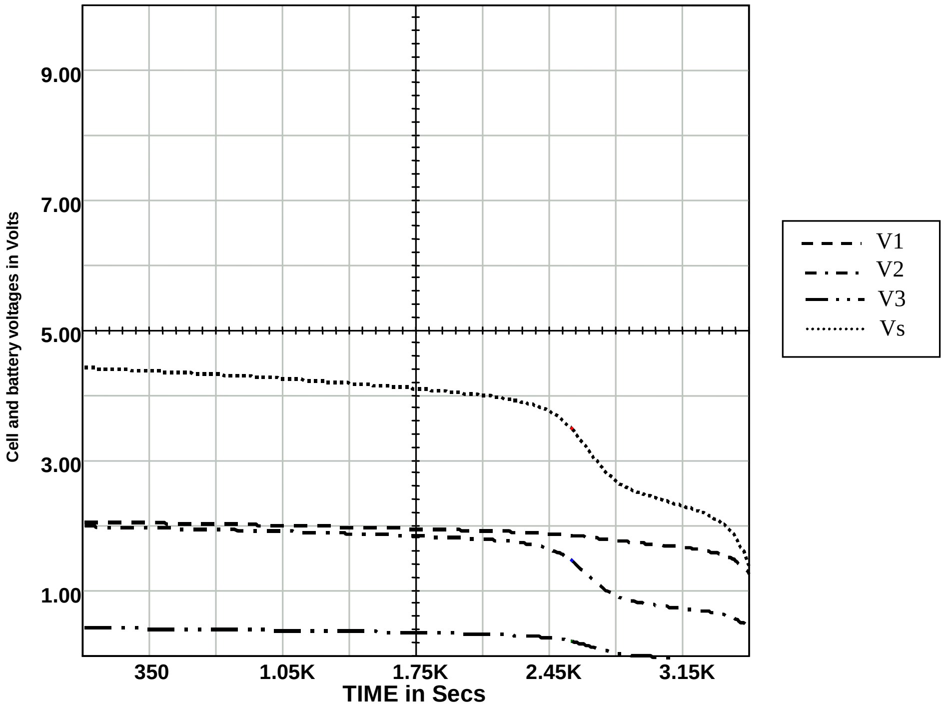

Fig. 4: Simulated discharging characteristics of two 6 Ah cells with initial charge of 5.5 Ah (V1) and 4.5 Ah (V2) and one disconnected cell (V3).

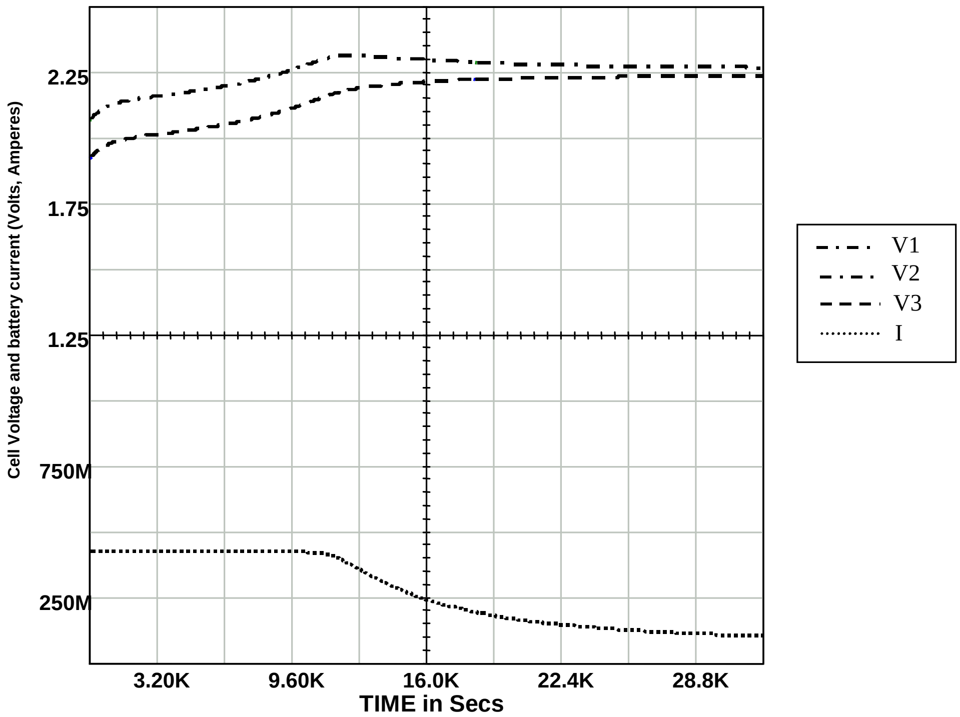

Fig. 5: Simulated charge characteristics of cells V1 and V2 (upper curve) and V3 (disconnected cell) under constant current – constant voltage charge.

5. Experimental Verification

In order to verify the operation of the proposed equalization technique, during charging and discharging operation, a prototype circuit for three-cell equalization was implemented in the laboratory. A common type high-frequency, ferrite-core transformer is built using the Siemens EC 52, N27 core rated at 275 W @ 25 kHz, with 2 turns for each half of each center-tapped coil. The transformer operates at 25 kHz and its rated power is 30 W. This agrees with the concept stated in section 3 to keep the leakage inductances low enough so to be neglected. A Yuasa 6N6 fluid type battery was used, modified to allow external electrical connections to cell terminals. The system was subjected to several bulk charge and discharge runs and the impact of several non-uniformities was examined.

When the cells were equalized using the proposed technique with open battery terminals, only a very low current passed through them (a few mA) and the system operated as expected. Under constant current charge conditions, an almost time-independent current difference appeared among the cells (before full charging occurred), as expected.

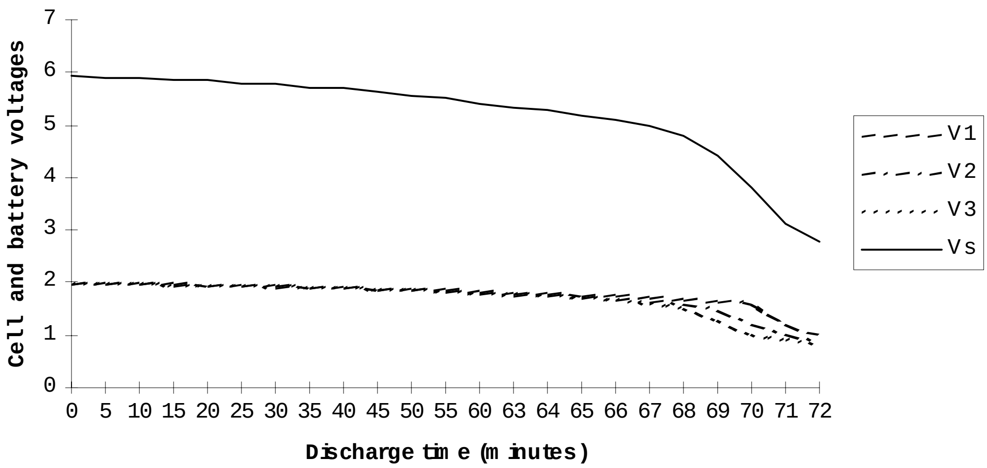

Fig: 6. Discharging equalization for the three cells.

The experimental discharging characteristics for three equalized cells are shown in Fig. 6. It is observed that all three cells follow a normal discharging operation curve and reach their discharging point at almost the same time, around 69 minutes after discharging initialization.

With one cell disconnected, the proposed system maintains the full cell voltage under no load conditions. The experimental discharging characteristics under load are shown in Fig. 7. Discharging was stopped when the voltage across the disconnected cell terminals became negative.

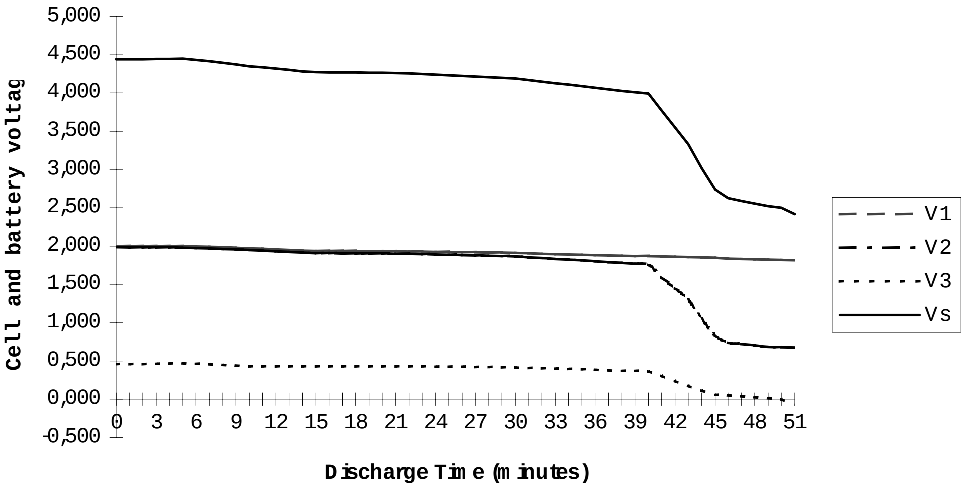

Fig. 7. Three cells discharging equalization with one cell disconnected.

The experimental conditions of Fig. 7 are close to the worst case, since for a battery of only 3 cells one cell is disconnected, thus the remaining two cells must provide the total required power. The load is supported for about 40 minutes with a voltage higher than 4V, which is considered to be the minimum allowable operating voltage of the load.

Experimental results have shown that in the case of high rate discharging, the good cells had different discharging rates. The discharging rate of those cells which first reached deep discharging became much lower than that of the rest. In this way, all cells reached deep discharging without reverse polarizing effects.

The experimental bulk charge characteristics under constant current - constant voltage conditions, but with one cell disconnected, are shown in Fig. 8.

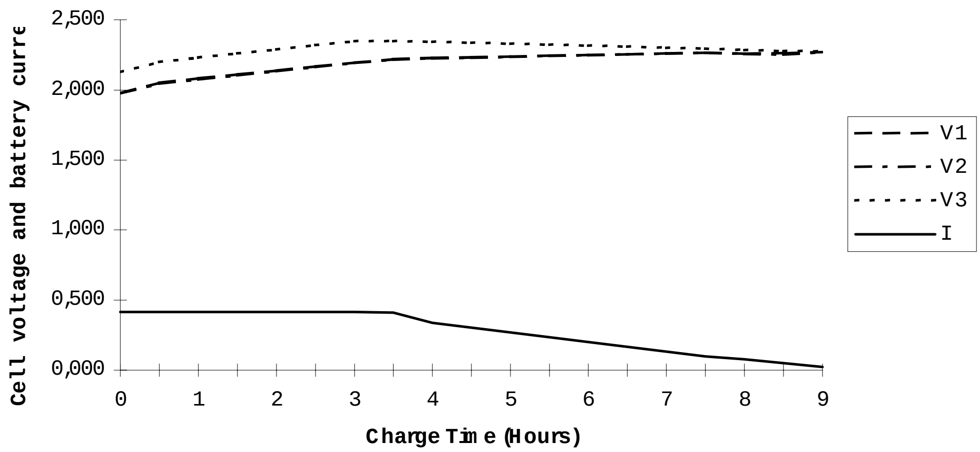

Fig. 8: Bulk charge equalization for three cells with one cell disconnected.

As shown in Fig. 8, the open cell terminal voltage is relatively high but the voltage differences of the battery cells become lower as the charging current decreases.

6. Conclusions

A new equalization technique has been presented which overcomes some of the most significant operation problems found in a string of series connected battery cells. Charge equalization, prevention of cells reverse polarization during discharging and system fault tolerance are the major advantages of the proposed technique. The operation of the proposed technique has been verified both by simulation results, using the SPICE simulation program, and by experimental results. The modular construction and the variety of operation modes characterize the flexibility of the proposed technique. The equalization unit, in cooperation with a Battery Management System (BMS), forms a programmable system that can easily be adapted to the specific needs of any type of battery.

The modularity of the proposed scheme allows the expansion of the system for charging and discharging equalization of any number of battery units. The operation of the 3-cells experimental model used for the evaluation of the proposed method, proved the functionality of the system and revealed the problems related with the implementation of the system. These problems can be overcome with the necessary compromises relevant to each specific case and the unit control capability can be extended to an adequate number of cells.

6. References

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