A New Equalization Scheme for Series Connected Battery Cells

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Abstract

In this paper a new equalization scheme for series connected battery cells or monoblocks is presented which provides both charge and discharge equalization. The equalization scheme described in this paper provides support for the battery operation even with damaged cells, ensures a uniform battery cell voltage fall, thus protecting cells from reverse polarization, and maximizes the energy delivered by the battery (Fig. 2). An evaluation Battery Management System (BMS) was developed in the laboratory, utilizing the proposed equalization scheme, and the experimental results verify the theoretical ones.

Introduction

There is 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 [1-7]. With most of these schemes, discharge 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 discharge equalization is used the following problems may exist:

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

Although the scheme proposed by [1], which is shown in Fig. 1, can re-circulate energy and maintain the terminal voltage across an open-circuited cell exhibits the following disadvantages:

– It is an expensive method, because each cell needs a separate bi-directional DC/DC converter.
– Since each DC/DC converter has its own control circuit, this scheme exhibits high control complexity.
– Since each bi-directional DC/DC converter utilizes a separate transformer or inductor, this results to a low power density system. In the rest of the equalization schemes found in literature [2-7], no discharge equalization is used at all.

The need of a simple scheme that can be applied to homogeneous cell strings, regardless of the string chemistry or cell voltage and can provide both effective charge and discharge 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 (H.F.) transformer. The main advantage of the proposed scheme 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 discharge requirements.

System design considerations

The proposed equalization scheme 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 (Fig. 2).

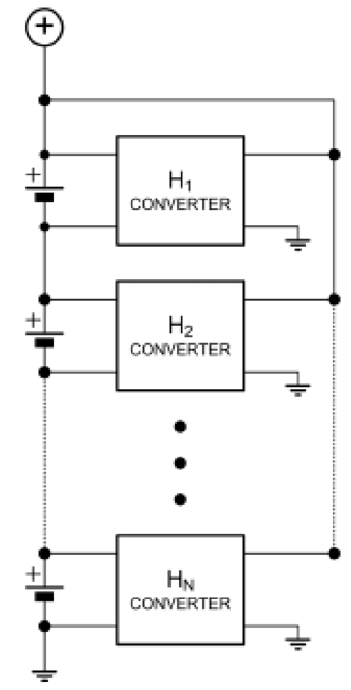

Fig. 1: Equalization scheme proposed by [1]

Each center-tapped winding is connected to two adjacent battery cells through four switch-diode pairs as shown in Fig. 2. 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. This is the desirable situation and can be achieved only if power MOSFETS are used as switches. Power MOSFETs are able to utilize bi-directional switches having controllable 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 multi-winding transformer, which drives all MOSFET-switches shown in the circuit of Fig. 2. All MOSFETs stay in an '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 the next section (Charging Operation analysis). In cordless tools powered by rechargeable battery packs, where the weight is a significant parameter, the module coupling transformer winding shown in Fig. 2 is not used. Thus, the rest of the circuit is used only for discharge 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.

Discharging operation mode

To apply discharge 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 discharge 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 [10]. 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.

Charging operation mode

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

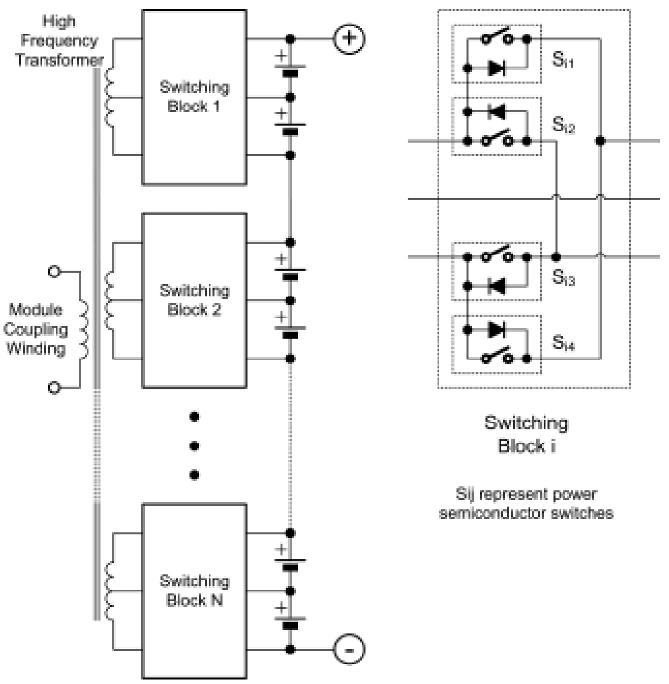

Fig. 2: The basic diagram of the proposed scheme

through which these cells are equalized [3, 8, 9]. 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 charge-discharge equalization scheme 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. A BMS that incorporates a charge-discharge equalization scheme can control the electromechanical type fuses. The current sensing for each battery can be done indirectly with a main battery dc current sensor and a current sensor for each switch-diode pair.

The proposed scheme applies two types of charge equalization. The first type operates the power semiconductor switches as in discharge equalization mode, thus giving low DC ripple. This type of equalization must be used if defective cells are present and with this type of equalization the full rated transformer power can be used. This type of charge equalization is suggested since it is the most efficient.

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 can be 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 scheme 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.

When the power semiconductor switches are operating, all the cells of a module can be removed. In that case, the module will generate a percentage of the removed cells' voltage with power flowing through the module coupling windings. In this type of coupling there is higher influence of the leakage inductance, since different cores are coupled. In higher power or higher switching frequency systems the module coupling windings path inductance may be a problem. Elimination of path inductance effect can be achieved by switching the coupling path to a DC voltage. This can be obtained by connecting the module coupling windings with its coupling path through a MOSFET bidirectional active rectifier.

It is apparent that the proposed equalization method does not reduce the number of cell windings compared to that of [4], but offers all-cell equalization in both half cycles of the switching converter operation.

System analysis

As described above, during the discharging period the MOSFET switches in Fig. 2 are turned ON and OFF alternatively, in order to connect each pair of cells with the respective transformer winding. Each state lasts for exactly half a cycle, thus the average magnetic flux inside the transformer becomes zero. Under the assumption that all cells have the same voltage, the windings have the same voltage and only a low magnetizing current flows through them. The current path is through the cells and the main losses consist of the driving losses of the switches.

Discharging operation analysis

If a battery cell cannot supply the required current, then the remaining battery cells supply the additional current through the H. F. transformer. The leakage inductance of each transformer winding increases the converter output internal resistance. The resistance R_{COIL} represents the total winding contribution to the converter internal resistance.

In case that M cells out of a total number of N are totally defective, then the $N - M$ cells apply additional current, $M \cdot I_L$ Amps, to the transformer, in order to provide the additional required current of the M missing (i.e. defective) cells. Therefore, since each good cell supplies $(M \cdot I_L)/(N - M)$ Amps additional current (through the switches), the total voltage drop, V_T, which appears across R_{DSON} and R_{COIL} is given by:

$$V_T = \frac{M \cdot I_L}{N - M} \cdot \left(R_{DSON} + R_{COIL}\right) \tag{1}$$

Moreover, regarding Fig. 3 and using Eq. 1 the voltage across each defective cell winding, V_W, is given by:

$$V_W = V_B - \frac{M \cdot I_L}{N - M} \cdot \left(R_{DSON} + R_{COIL}\right) \tag{2}$$

When the MOSFET that connects the terminals of one defective cell to the respective winding forces its antiparallel diode to conduct, then Eq. (2) can be combined with Eq. (1) to obtain the defective cell terminal voltage which given by:

$$V_C = V_B - V_F - V_T - (R_D + R_{COIL}) \cdot I_L \tag{3}$$

where:

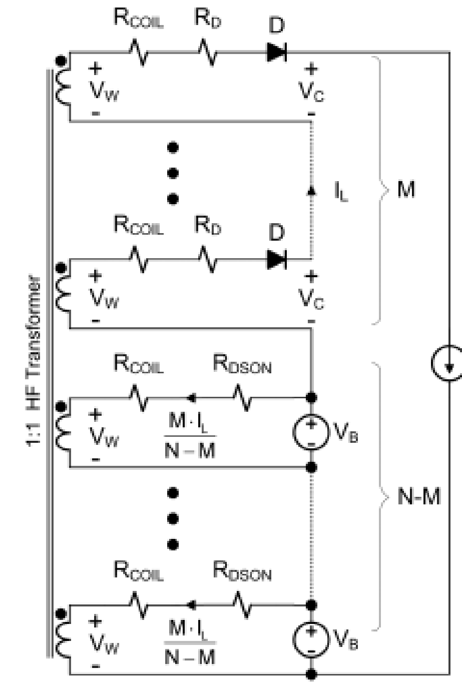

Fig. 3: The battery discharging equivalent circuit

– V_F is the forward diode voltage drop (assuming that the MOSFET switch allows diode conduction);
– R_D is the diode forward resistance.

Finally, regarding Fig. 3 and using Eq. (3) the total battery voltage V_S is given by:

$$V_S = (N - M) \cdot V_B + M \cdot \left[V_B - V_F - V_T - \left(R_D + R_{COIL}\right) \cdot I_L\right] \tag{4}$$

or after rearranging Eq. (4) yields to:

$$V_S = N \cdot V_B - M \cdot \left[V_F + V_T + \left(R_D + R_{COIL}\right) \cdot I_L\right] \tag{5}$$

Eq. (5) is used to determine the maximum allowed number of defective cells, while the battery voltage is kept above the minimum load operating condition. It should be pointed out that Eq. (5) is not valid if the MOSFET voltage drop is less than V_F and the diode, which is in antiparallel with the MOSFET switch, is not conducting. In this case it is $R_{DSon} \cdot I_L < V_F$, thus the quantity $V_F + R_D \cdot I_L$ is replaced by $R_{DSon} \cdot I_L$. This is the desired case, but V_F is not significant in a battery-based variation of the proposed equalization scheme.

Charging operation analysis

During bulk charging, a similar operation takes place as in the discharging equalization case. The current difference of the higher voltage cells is distributed through the switches and the transformer to the lower voltage cells. The distributed current is low due to the following reasons:

– the voltage difference between the higher and the lower voltage cells is low during charging and
– the charging current is much lower than the discharging current.

Therefore, the conduction voltage drop on the MOSFETs can be neglected, and since the RDSON is much lower than the internal resistance of a charged cell, it is assumed that all cells are charged to the same voltage. This is useful for charging lead-acid batteries, but even in this case, the temperature and current of each cell must be continuously monitored to avoid battery overheating. Usually, bulk charging is performed under constant current conditions with all cells connected in series, a configuration that can be implemented in the proposed equalization scheme by turning all switches off. The main problem of the above situation is that a defective cell (open circuit) can block the charging of the whole battery. If this is the case, the proposed system can be activated for charging equalization and the maximum cell current can control the total battery charging current.

When one of the cells reaches the threshold voltage, the trickle charging mode is activated for the whole battery. The switches go to the 'OFF' state and the converter connected to the module coupling winding resumes the charging equalization procedure [4]. Since, during this phase of charging, the power delivered by the converter is considerably lower, then the ramp current waveform provided by the ramp converter and the converter varying frequency do not violate the transformer rated power limit. After full charging and during the battery rest period, a capacitor connected in parallel with each cell retains the voltage across a defective cell. Since the charge stored in the capacitor is very low compared to that of the cell, more frequent short periods of trickle equalization are needed.

Integration with a battery management system (BMS)

From the previous system 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 scheme can be controlled by a BMS to provide discharge equalization during the whole discharging period, or only if a cell voltage reduces below a threshold level. During the charge period, the BMS must be able to control the charger and the proposed system can operate under the following modes:

– charge all cells in series with all power semiconductor switches open,
– charge all cells under the same voltage with non-controlled charging current,
– 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 BMS will isolate defective cells (separately or the entire monoblock) by utilizing the integrated electromechanical fuses. The fuse function is served by latch relays, which are commanded simultaneously with the converter, for isolation and equalization. The BMS reaction time in such a condition depends mainly on its topology and on how fast it has been designed to manage fault interrupts. Even in low computation speed systems with one processor that does not use interrupts, which is the case in the experimental prototype, the required time is estimated to be fraction of a second. When the converter starts, the system operates in a fault tolerant mode, providing charging and discharging equalization continuously, depending only on the battery operation mode.

The exact control algorithm that the BMS will use 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 [11]. 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.

System design implementation

A cell-based 36 V lead-acid battery BMS was constructed specified to manage a string of three 12 V 45 Ah fluid-type batteries. An individual battery module, based on a separate transformer, was used to equalize the battery cell voltages and all the transformers were coupled by their coupling windings. Each transformer was built utilizing an E65/32/37 ferrite core and the operation frequency was 16 kHz. The windings were wound one next to the other in a single layer, for uniformity and equality of leakage inductances purposes. The equality of leakage inductances in this system is not so critical as in a charge-only equalization system.

The module coupling winding were wound in 1 by 1 and side by side fashion with the equalization windings in order to achieve uniformity and low leakage inductance. As a result, the module coupling windings connection path has a peak voltage almost equal to a single battery voltage. IRFZ44 MOSFETs has been utilized.

In the proposed equalization scheme during the charge equalization the transformer operates at only in a part of its rated power and shows up much lower leakage inductance compared with a smaller transformer that operates at 100 % of its rated power. During the discharging period it is efficient to start the equalization at the moment that a battery cell reaches the deep discharge. In this case the state-of-charge levels between the cells have big differences and the increment of the discharged cells internal resistance mainly determines the current flows. The block diagram of the battery module is shown in Fig. 4. A microcontroller (MCU) board controls the latch relays, the equalizer and the multiplexer through the MCU board connector. Also, it communicates with the A/D converter and the temperature sensors. Every battery module supplies the MCU board through an isolated DC/DC converter.

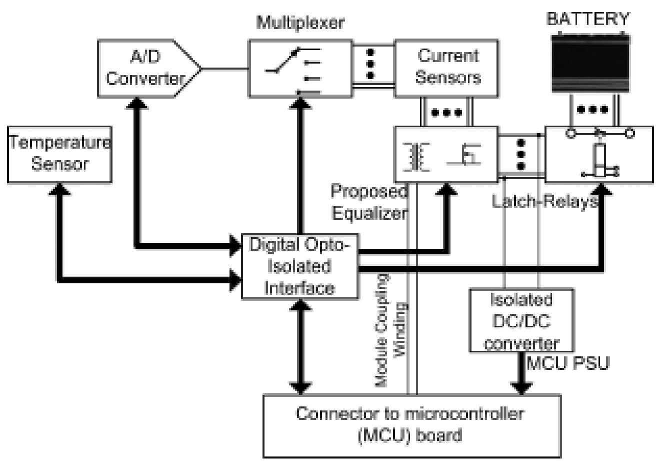

Fig. 4: Block diagram of the experimental Battery Module

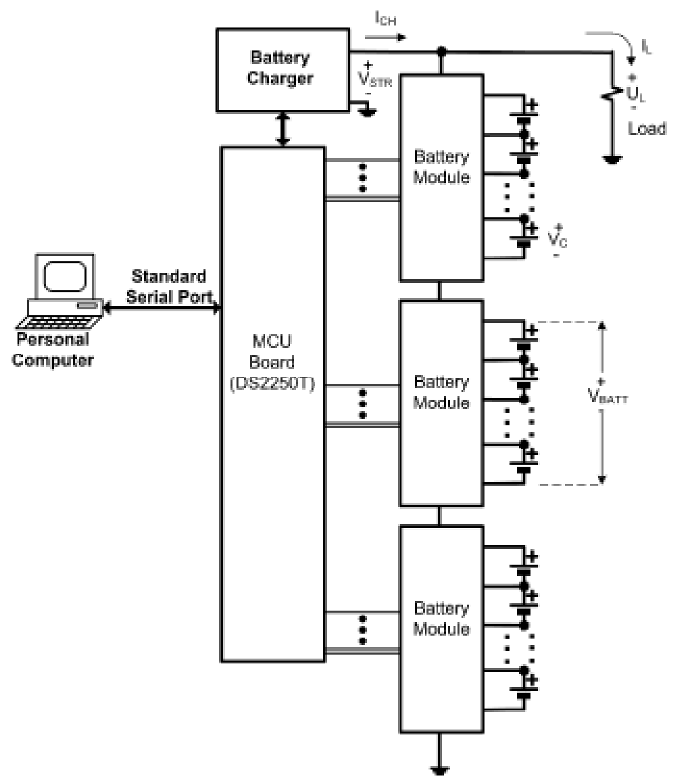

Fig. 5: Block diagram of the experimental Battery Management System

The constructed BMS block diagram is shown in Fig. 5. It was designed to communicate with a Personal Computer (PC) through a serial port and a specially developed computer program was logging one measurement set per minute into a file. The battery string was tested both during charge and discharge. An adequate number of curves, which validate the beneficial results of charge and discharge equalization, were acquired.

Experimental results

In order to verify the state of health (SOH) of the battery string, the experimental curves of the battery string during discharging and without equalization, are shown in Fig. 6. The discharge current is about 4.5 A.

Observing the curves of Fig. 6, yields that the worst cell of the string is the cell No. 3 of Battery No. 3 and the healthiest battery is the Battery No. 2.

In contrast to the above curves, the discharge curves of the battery string under discharge equalization operation with the same load and with Battery No. 3 disconnected are depicted in Fig. 7. The batteries initial state of charge is set to be the same as in the previous case of Fig. 6.

According to the experimental results of the BMS, the benefits of the discharge equalization are apparent. The measurements show that for the specific battery string, when the two batteries are connected and discharge equalization is used, the load can be supplied for longer time than with all the three batteries connected without using discharge equalization. The cells are also protected from reverse polarization and the theoretical expectations are fully confirmed. The case that all batteries are connected and discharged with discharge equalization is shown in Fig. 8. Thirteen (13) minutes after the start of discharging the cell No. 3 of Battery No. 3 reaches the threshold voltage and the BMS starts the equalization. This set of measurements was taken before the set of measurements that is shown in Fig. 6 and this is the reason that this cell has a better SOH here. The cell No. 3 of Battery No. 3 was become gradually totally useless during the tests.

Comparing the experimental discharge curves with and without equalization, the effect of the equalization is visible. The load voltage remains above 30V for more than 275 minutes and the total battery string voltage curve is smooth. In this case, the discharge equalization causes the string to deliver about double energy, compared to the discharge without equalization. It is noted that the difference in the delivered energy from the previous case, in which Battery No. 3 was disconnected, is in a part only the energy of the Battery No. 3. The other part comes from the lower energy that is dissipated due to the lower currents on the equalizer and from the batteries bigger capacity due to the lower current discharging.

The experimental bulk charge characteristics under constant current – constant voltage conditions, but with Battery No. 3 disconnected are shown in Fig. 9.

The maximum battery string charging current is set at 2/3 of C/10 and the final charging voltage is set on purpose relatively high.

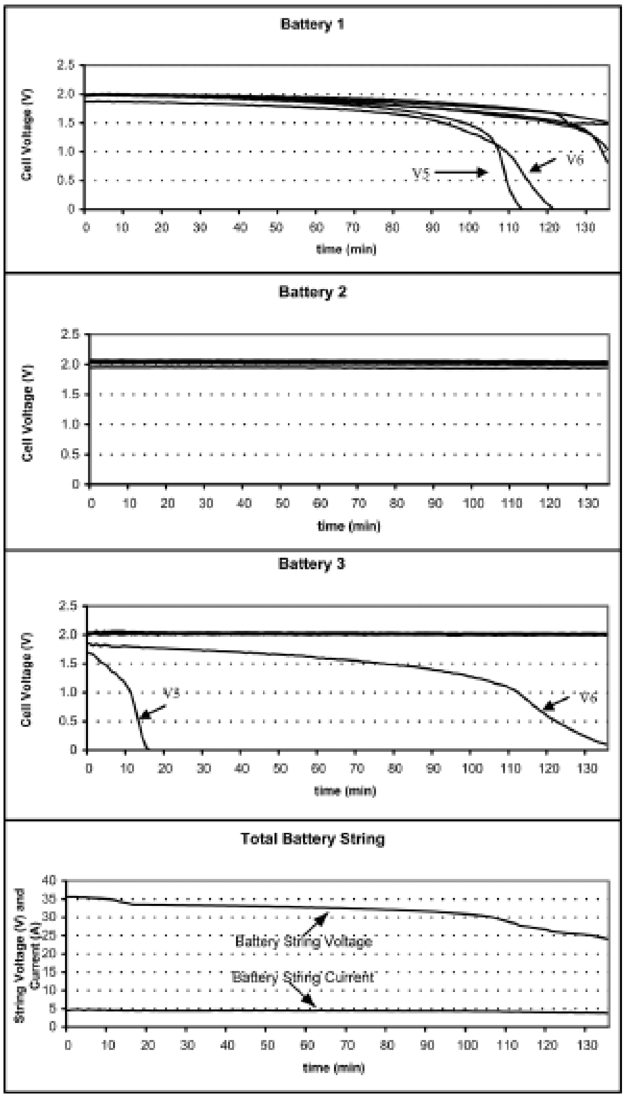

Fig. 6: Experimental discharge curves of three 6 cells batteries without equalization

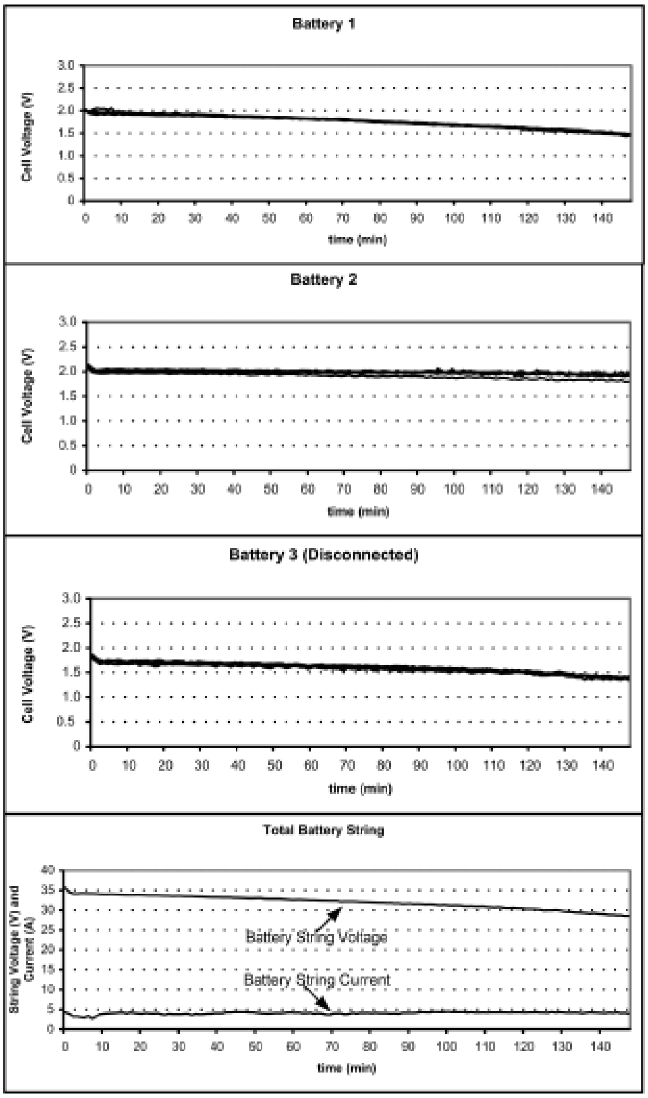

Fig. 7: Experimental discharge curves of a BMS, developed for three 6 cells batteries, with one battery disconnected

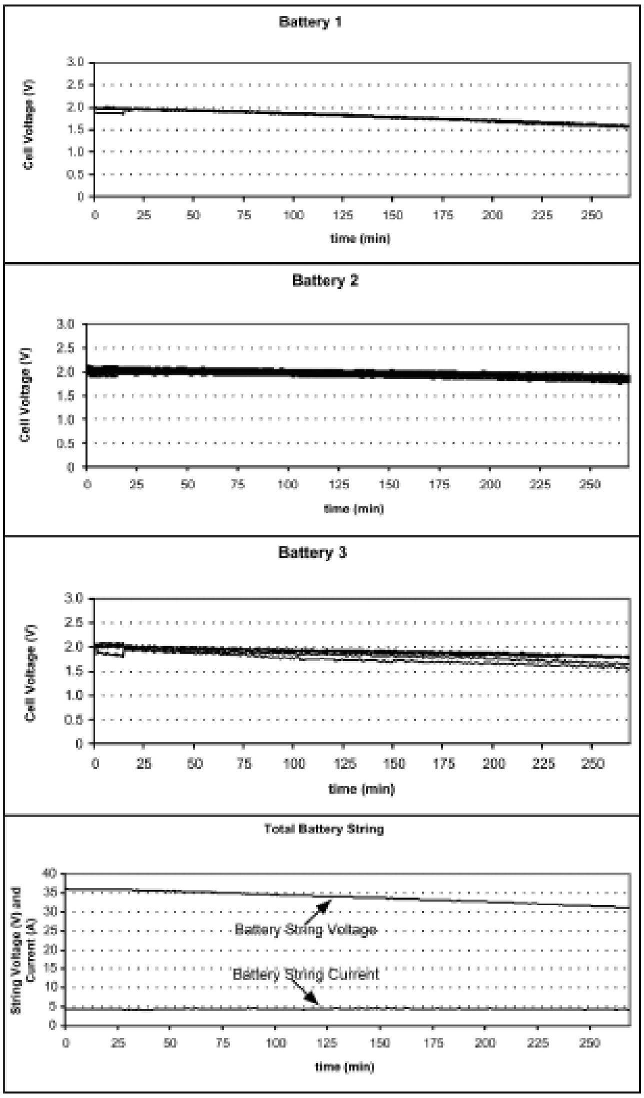

Fig. 8: Experimental discharge curves of a BMS, developed for three 6 cells batteries, with equalization started when minimum cell voltage is 1.8 V

The final string current is close to 1A. Even in this extreme case the voltages of all the cells have not big differences, which become smaller as the charging current decreases.

Conclusion

A new equalization scheme 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 scheme. The modular construction and the variety of operation modes characterize the flexibility of the proposed scheme. 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 design flexibility of the proposed scheme makes it appropriate for a wide range of applications such as Photo-Voltaic (PV), Uninterruptible Power Supply (UPS) and low power portable systems. In high power non-stationery applications the weight of the equalization converter may be considerable. However the continuing reduction of both size and weight of power electronic systems due to the adoption of higher switching frequencies and application-specific ICs, enable the expansion of the method to EV applications.

References

[1] S. T. Hung, D. C. Hopkins and C. R. Mosling: Extension of Battery Life via Charge Equalization Contro, IEEE Trans. on Industrial Electronics Vol. 40, No. 1 Feb. 1993.

[2] N. Kutkut, D. Divan, D. Novotny: Charge Equalization for Series Connected Battery Strings, IEEE Trans. on Industry Applications Vol. 31, No. 3, May/June 1995.

[3] N. Kutkut, H. Wiegman, D. Divan, D. Novotny: Charge Equalization for an Electric Vehicle Battery System, IEEE Trans. on Aerospace and Electronic Systems Vol. 34, No. 1, Jan 1998.

[4] T. Z. Gottwald, YE. T. Stuart: Equalization of EV and HEV Batteries with a Ramp Converter, IEEE Trans. on Aerospace and Electronics System Vol. 33, No. 1, Jan 1997.

[5] C. Pascual, P. Krein: Switched Capacitor System for Automatic Series Battery Equalization, Proc. of APEC 97-Applied Power Electronics Conf., 1997, vol. 2, pp. 848-54.

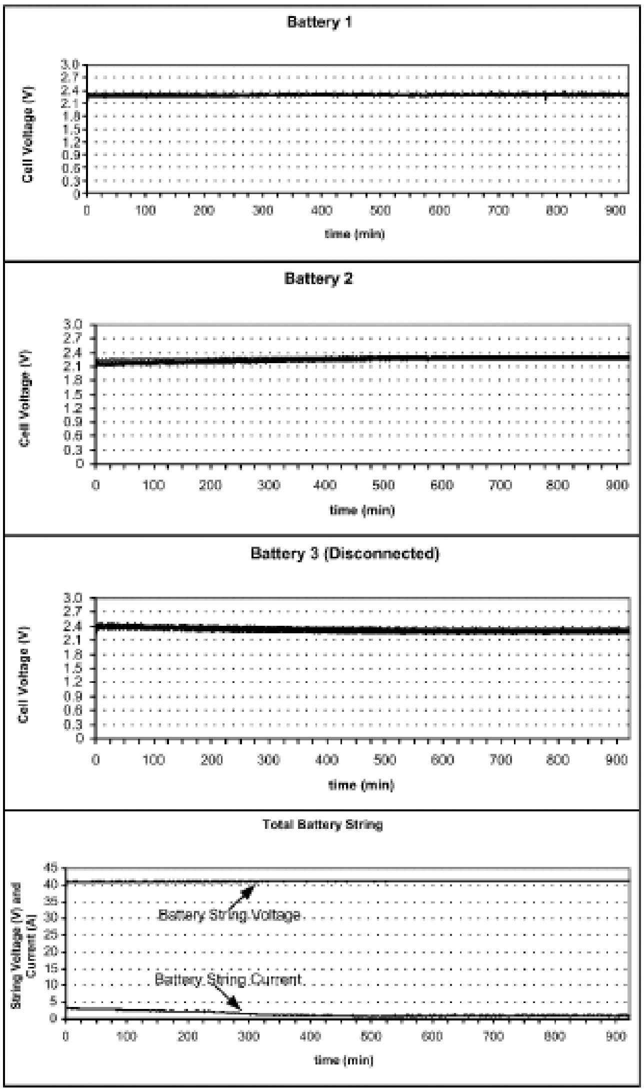

Fig. 9: Experimental bulk charge curves of a BMS developed for three 6 cells batteries, with one battery disconnected

[6] N. Kutkut, D. Divan, D. Novotny: Charge Equalization for Series Connected Battery Strings, IEEE IAS Annual Meeting Conference Record, Denver, CO, Oct. 1994, pp. 1008-1015.

[7] N. Kutkut: A Modular Non-Dissipative Current Diverter for EV Battery Charge Equalization, Proc. of INTELEC 96-International Telecommunications Energy Conf., Boston, MA, Oct. 1996, pp. 514-21.

[8] N. Kutkut, H. Wiegman, D. Divan, D. Novotny: Design Considerations for Charge Equalization of an Electric Vehicle Battery System, IEEE Trans. on Industry Applications, Jan/Feb 1999, Vol. 35, No. 1, pp. 28-35.

[9] N. Kutkut, H. Wiegman, D. Divan, D. Novotny: Design Considerations for Charge Equalization of an Electric Vehicle Battery System, Proc. of 1995 Applied Power Electronics Conf. and exposition-APEC' 95, Dallas, TX, USA, 1995, Vol. 1, pp. 96-103.

[10] Z. M. Salameh, M. A. Casacca, W. A. Lynch: A mathematical model for lead-acid batteries, IEEE Trans. on Energy Conversion, Vol. 7, No. 1, March 1992.

[11] J. Chatzakis, K. Kalaitzakis, N. Voulgaris, and S. Manias: Designing a New Generalized Battery Management System, IEEE Trans. On Industrial Electronics, Vol. 50, No. 5, October 2003, p. 990-999.

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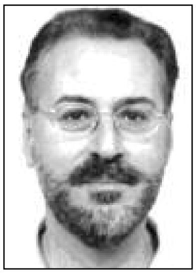

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