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Increased Performance of Battery Packs by Active Equalization

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Abstract— **Battery packs for most applications are series strings of electrochemical cells. Due to manufacturing variations, temperature differences, and aging, the individual cells perform differently. When a complete pack is charged and discharged as a single two-terminal circuit element, some cells are chronically overcharged, undercharged, or overdischarged, all of which act to reduce cell life. The performance and life of the complete pack is limited by the weakest cell. Many methods have been proposed and explored to mitigate this problem. In the present work, a switched-capacitor converter is shown to be a simple and effective method to maintain equal cell or monoblock charge conditions. Design criteria are discussed.**

Index Terms— **Battery Equalization, Battery Pack, Electric Vehicle**

I. INTRODUCTION

Most applications for batteries require higher voltage than can be obtained from a single electrochemical cell. For example, a 12 V lead-acid battery is composed of six individual cells in series. Other secondary battery chemistries, such as nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), and lithium-ion types, are generally manufactured as individual cells that are then connected in series and parallel to generate the correct voltage and energy storage. Telecommunications energy applications often use 48 V strings. Other applications, such as electric vehicles, uninterruptible power supplies (UPSs), and off-grid solar energy systems, call for voltages ranging from 12 V nominal to 300 V or more. The high end of this range is most common in electric traction, while the low end is found in consumer-grade UPSs.

The individual cells within a battery string differ due to manufacturing variations, temperature gradients, and aging effects. If the string is treated as a two-terminal device while being charged and discharged, the individual cells will have different states of charge (SOC). Some cells will be chronically overcharged, undercharged, or overdischarged. Over many cycles, this tends toward capacity decrease for the cell and the pack. Sophisticated battery users are aware that SOC balance is necessary, particularly for valve-regulated lead-acid (VRLA) and lithium-ion types [1-7]. For flooded lead-acid batteries, at least in low voltage strings, overcharge equalization is a standard approach in which the battery pack is occasionally overcharged to ensure that no cells are undercharged. This is a potentially damaging process that leads to water loss. In VRLA or lithium-ion batteries, the potential for damage is much greater. Lithium-ion batteries pose a significant safety risk if overcharged.

Ideally, battery cells or monoblocks should be equalized on the basis of SOC. However, this requires detailed modeling of each element of the battery string. Terminal voltage is an adequate surrogate for SOC for balancing purposes. Open-circuit voltage is a nonlinear, but monotonic, function of SOC [4], with a reasonably high slope for lead-acid and lithium-ion cells. So if open-circuit voltages are matched, the monoblocks will have equal SOC. Under load, terminal voltage will vary significantly from open-circuit voltage due to battery internal impedance, which is again a nonlinear function of SOC. If all of the cells or monoblocks in a battery string are properly maintained through equalization and maintenance, their internal impedances should be nearly equal. Also, if the equalization current is small, the individual currents will also be nearly equal. Therefore, equalized terminal voltages should correspond to nearly equalized open-circuit voltages and states of charge. Voltage-based equalization is most effective when the battery is at rest, e.g., at the end of a charge or discharge cycle. These regimes also correspond to the maximum slope in the relation between voltage and SOC.

Many passive and active methods have been proposed to replace overcharge equalization with voltage-based equalization. In [8], the most common method is described in which dissipative elements (either a resistor or a transistor operated in its linear regime) is switched on across individual cells as they reach the maximum allowable voltage. There are many drawbacks to this approach. Since it is dissipative, this technique sacrifices substantial energy and does not scale well to large battery packs. That is, dissipating a few watts in a 2 Ah battery string is easily manageable, but dissipating a few hundred watts in a 200 Ah string is challenging. Also, the clamp only affects the top end of the charge cycle. This provides no protection against overdischarge and would have no influence on the performance of a battery string that is not fully charged. Typically the voltage setting for action is predetermined and fixed, and cannot be adjusted for temperature compensation or adapted easily to various chemistries. The primary advantage of a dissipative technique is its simplicity.

Direct clamping methods, equivalent to placing a zener diode across a cell or monoblock, are also common. They share the characteristics of dissipative methods. The added advantage is that this technique is passive, and functions

without sensing or external control.

As an alternative to dissipative methods, active methods that employ switching power techniques have been introduced. Most active methods for equalization are built around standard or modified dc-dc converters. Some are isolated, using forward [2, 7, 9-16] or flyback [17] converters. The isolated approaches tend to be voltage-controlled. The approach of [11] uses an input-side voltage control and relies on precision transformers with many windings to balance individual monoblocks. Others use a buck-boost [18-23] or boost-buck [24] converter. A recent variation is to use a buck-boost converter but with a resonant tank in place of the inductor, for a quasi-resonant zero-current-switching converter [25]. This is essentially equivalent to the quasi-resonant version discussed in [26]. The non-isolated dc-dc converter approaches tend to focus on current control—sensing a difference between cell or battery voltages and driving positive or negative current to drive the difference to zero. They all share the need for magnetic components, whether inductors, transformers, or coupled inductors.

Dc-dc converters for equalization can be configured a number of ways. In a modular approach, each converter equalizes two adjacent batteries. The total system requires one fewer module than there are monoblocks. Alternatively, the complete equalization system can be built to recirculate power. Each monoblock then has a unidirectional converter that ultimately discharges the monoblock into the whole string. This approach relies on supervisory control to keep the recirculating power to a minimum. If equalization is only needed during charge, a special charger could be built instead that divides the full charge voltage into equal voltages for each monoblock. Different converter topologies are more relevant for one of these three approaches, which are discussed in [27].

Switched-capacitor (SC) converters provide an alternative to magnetic components, and are widely used at modest power levels [28]. An SC converter for battery equalization [26, 29-32] has been discussed for VRLA and lithium-ion applications [3, 5, 6, 33]. The present work discusses the operation of the proposed SC converter and design requirements for float and cycling applications.

II. THE SC EQUALIZER

The basic SC equalization circuit is shown in Fig. 1. In an equalization application, voltage regulation is not necessary. If the two pairs of switches in the SC converter are operated with identical duty cycles, the voltage conversion ratio will be 1:1, precisely the desired ratio for equalization. There are two sets of capacitors. The capacitors directly across the battery terminals decouple inductance in the battery leads, while the others are switched to perform equalization. There are two sets of switches. Set one (G1) connects the switched capacitors to all of the positive battery terminals, while set two (G2) connects the switched capacitors to all of the negative battery terminals. The two sets are switched alternately. When the switches in set one are all closed, the switched capacitor voltages approach battery voltages 2 through n,
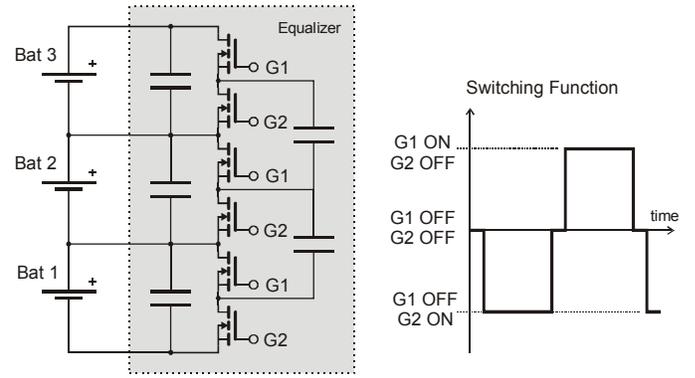

Fig. 1. Basic 3-cell SC Equalizer.

where n is the number of batteries. When the switches in set two are all closed, the switched capacitor voltages approach battery voltages 1 through n-1. The switched capacitor voltages do not change much, but are switched at a high enough frequency to move charge between adjacent batteries. Consider, for example, 470 µF being switched through 30 mΩ at 50 kHz and 45% duty cycle between two batteries that differ by 100 mV. The capacitor voltage will only change by 31 mV, for a net charge of 14.5 µC each cycle. At 50 kHz, though, the net current flow is 725 mA, for an equivalent resistance of 138 mΩ. The direction of current flow will depend on the relative voltages of the adjacent batteries and may vary throughout the pack.

III. PERFORMANCE MODELING

In [34, 35], a modeling method for SC converters was discussed. Fig. 2 shows the equalizer of Fig. 1 developed into an appropriate model. In the end, the SC converter behaves like a resistor shorting two adjacent batteries together. From [35], the equivalent resistance with equal duty cycles $D_1 = D_2 = D < 0.5$ is

$$R_{eq} = \frac{1}{fC} \frac{1 + \exp\left(\frac{DT}{\tau}\right)}{1 - \exp\left(\frac{DT}{\tau}\right)} \tag{1}$$

where $\tau = R_{total}C$, R_{total} is the sum of all resistance sources, and $T = 1/f$ is the switching period. A plot of equivalent resistance for a total capacitance of 470 µF and a time constant of 14 µs is shown in Fig. 3.

The total circuit resistance is composed of three main components: equivalent series resistance (ESR) of the capacitor, on-state resistance of the switches, and resistance of the interconnections. Reducing ESR can be accomplished in two ways. The total capacitance can be increased and the ESR can be decreased by simply connecting several identical
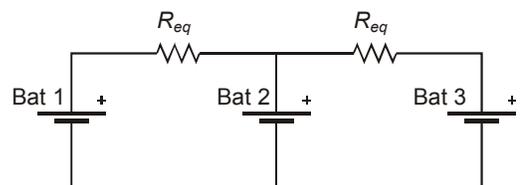

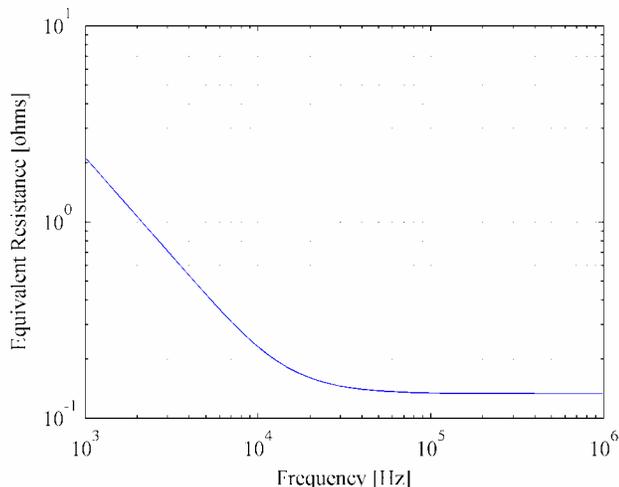Fig. 2. Equivalent model of a 3-cell equalizer.

Fig. 3. Equivalent resistance for a SC equalizer using a 470 μF capacitor, total resistance of 30 mΩ, D=0.45, as switching frequency varies.

capacitors in parallel. This approach does not improve the frequency characteristics but does reduce R_{eq}. Another important method for reducing ESR is proper component selection. Aluminum electrolytic capacitors generally have the worst ESR at a given capacitance, but are also generally quite small and are available at ratings exceeding 500 V. Tantalum capacitors have slightly better trade-offs but at increased cost. Ceramic and film capacitors can have quite low ESR but generally have small capacitance, so the circuit must operate at a higher frequency. Newer capacitor technologies, such as organic semiconductor-based or conductive polymer-based electrolytic types, have much better performance but with increased cost, lower availability, and low voltage ratings. The general trends shown in [35] indicates that designers should operate at a frequency approximately at $f = 1/\tau$, so a designer should pick a capacitor technology with low ESR and high capacitance and with a time constant that corresponds to a desired operating frequency, as determined by other components in the circuit.

Switch on-state resistance can be a major contributor to R_{eq}. To achieve the goal of switching near $f = 1/\tau$, which will almost always exceed 1 kHz, semiconductor switches are required. Current flow is bidirectional with the most general assumptions about battery voltages. Current must be able to flow with small voltage differences. All of these requirements point toward the use of MOSFETs. Given normal battery voltages of 12 V or less, many low-voltage MOSFETs are available with static drain-source resistance $R_{ds(on)}$ of a few mΩ. As with capacitors, total resistance can be reduced by paralleling MOSFETs.

Interconnection resistance is usually a small but important contribution. Although the current in the circuit is generally small, printed circuit boards (PCBs) and wiring harnesses should be designed as if the current was much higher. For example, 25 cm of 12 AWG wire has a resistance of 1.3 mΩ. This is on the same order as the $R_{ds(on)}$ of a low-voltage MOSFET and can have a significant effect on an equalizer designed for only a few amps. Corrosion at wire termination points can also have a major impact. In particular, if some connections are more corroded than others, the corresponding batteries or cells will not be properly equalized, resulting in degradation similar to an unequalized pack.

Proper SC design relies on coordinating all three sources of resistance: capacitor ESR, MOSFET $R_{ds(on)}$, and interconnection resistance. The maximum performance possible from the converter [35] at high switching frequency is

$$R_{eq.\lim} = \frac{2R_{total}}{D} > 4R_{total}. \qquad (2)$$

In practice, D must be sufficiently less than 0.5 to ensure deadtime and prevent shoot-through in the MOSFET totem poles. Also, the converter is not switched infinitely fast. Performance of around $R_{eq} = 5R_{total}$ is a reasonable goal.

IV. PERFORMANCE REQUIREMENT

The preceding section explained the basic operation of the SC equalizer and ways to determine the performance of a particular design. A basic understanding of the battery chemistry is necessary to determine how much performance is necessary.

The primary goal of battery equalization is to keep the SOC of each battery matched. Lead-acid cells have a near-linear relationship between open-circuit voltage and SOC with a slope of 2 mV/% [36]. If the objective is to keep SOC within 5%, then voltage must be within 10 mV/cell. The equalization current must be sufficient to overcome the charging current during float, which is about C/100, where C is the capacity in Ah. Then the target equivalent resistance is

$$R_{eq} = \frac{\left(10\,mV/cell\right)\left(n\,cells\right)}{C/100} = \frac{n}{C}\,\Omega. \qquad (3)$$

For example, consider an application involving 12 V lead-acid monoblocks (composed of six cells each) rated for 50 Ah each. The target is $R_{eq} = 6/50\,\Omega = 120$ mΩ. This can be accomplished with a total resistance of 24 mΩ—low, but achievable with commercially available components.

The performance requirement for lithium-ion cells is much lower. According to [4], lithium-ion open-circuit voltage varies 8 mV/%. Float current approaches zero, but a current of C/100 near charge termination is probably appropriate. With a 5% matching requirement, the target equivalent resistance is

$$R_{eq} = \frac{\left(40\,mV/cell\right)\left(n\,cells\right)}{C/100} = \frac{4n}{C}\,\Omega. \qquad (4)$$

This allows an equalizer of ¼ the performance for the same number of cells per monoblock. While small lithium-ion packs are usually equalized on a per-cell basis, larger packs could be equalized on a per-monoblock basis.

V. EXPERIMENTAL SC EQUALIZERS

The application of SC techniques at low power levels has led to misconceptions that SC converters cannot handle high current and are inefficient. This arises from the use of SC methods in integrated circuits, in which capacitance values and parasitic resistances are limited by silicon area cost. When implemented on a larger scale, SC converters reach power densities and efficiencies similar to inductor-based switching

converters. For example, in [37], a 1 kW 42/14 V SC converter, built with six 4700 μF electrolytic capacitors, is demonstrated with an efficiency exceeding 96%. Another misconception is the idea that currents in SC converters flow as impulses. If the converter is switched at a low frequency, currents will be impulsive and performance will be poor. In a properly designed SC converter where $f = 1/\tau$, the currents will all be shaped like the first half-time-constant of an exponential decay. A simulation result is shown in Fig. 4.

Efficiency of an SC converter can be approximated using the equivalent resistance. Consider the above example, in which a 120 mΩ equalizer is used to move 500 mA at 12 V. The total power dissipation will be approximately 30 mW, while the converter is handling 6 W, for an implied efficiency of 99.5%. A practical converter at this operating point will have slightly lower efficiency when gate drive and control power losses are considered.

Equalizer efficiency is a poor metric, though. When an equalizer is continuously connected and operating on a battery through charge and discharge, cell voltages will remain close together. The current, and therefore the power being transferred, will decay to zero as the voltages approach each other. In this situation, an equalizer can be modeled as a small constant power drain—the power needed to switch the MOSFETs. Low-power design principles can reduce this drain to approximate the self-discharge of the battery pack.

Equalizers of various ratings have been built and evaluated. A small equalizer, designed for approximately the two 12 V, 50 Ah, lead-acid battery stack, measures 71 mm x 47 mm x 21 mm when packaged, for a total volume of 70 cm^3. This equalizer is pictured in Fig. 5. Its equivalent resistance is 150 mΩ. Fig. 6 shows battery voltages before and after this equalizer was enabled

A larger equalizer was built for a string of six 200 A-hr lead-acid batteries. It measures 175 mm x 150 mm x 37 mm when packaged for a volume of 971 cm^3. The equivalent resistance of this equalizer is 28 mΩ. Fig. 7 shows battery voltages before and after the equalizer is enabled.

VI. Conclusion

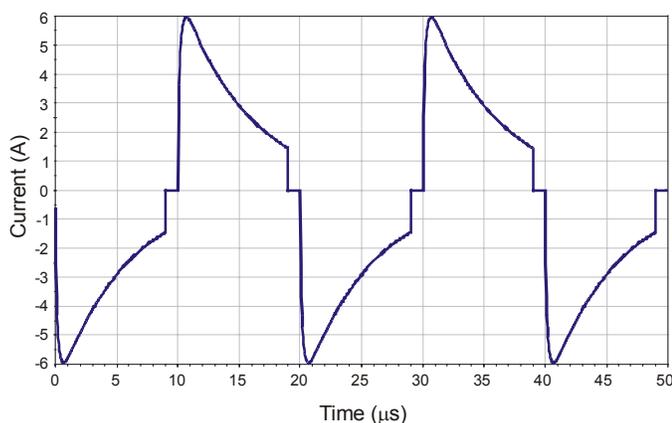A switched-capacitor equalization method was explained

Fig. 4. Current in the switched capacitor equalizer with a 0.1 V differential in the battery cell voltages. Capacitor is 470 μF switched at 50 kHz with D=0.45 and a total ESR of 30 mΩ

Fig. 5. Equalizer for two 12V lead acid batteries rated up to 50 A-hr
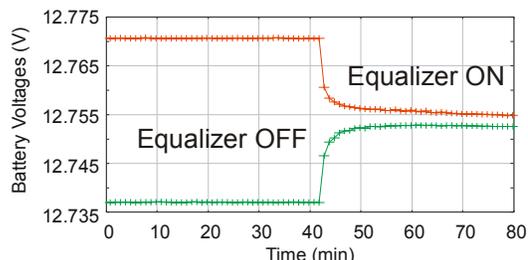

Fig. 6. Battery voltages before and after equalizer applied to two 12 V 50 A-hr lead acid monoblocks.
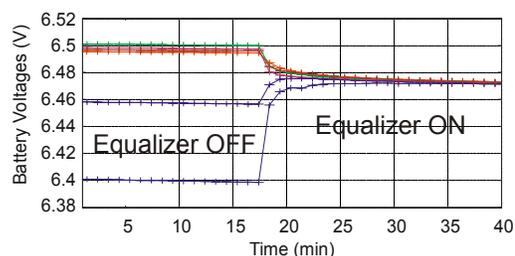

Fig. 7. Equalizer for six 6V lead acid batteries rated up to 200 A-hr

and demonstrated. A performance requirement was shown. Design approaches for achieving the required performance were discussed. Equalizers that achieve the appropriate equivalent resistance for two applications were discussed and demonstrated.

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