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***Abstract*— The auto industry is progressing towards hybrid and fully electric vehicles in their future car models. These vehicles need a power plant that is reliable during the lifetime of the car. Battery capacity imbalances stemming from the cell manufacturer, ensuing driving environment, and operational usage affect voltage levels, which must follow adherence to strict limits to ensure the safety of the driver. A variation on an existing method of using a capacitor to shuttle charge from one battery to another to balance series strings of batteries is proposed in this paper. The advancement shown in this paper is to bridge every two balancing capacitors with an additional capacitor, allowing for a balance time that is drastically reduced when compared to the original method. Simulation using an idealized model shows a substantial improvement in balancing time using the new topology.**

I. Introduction

The automobile industry uses high-voltage battery packs in many of its new fully-electric and hybrid-electric vehicles. These packs can employ large, high-voltage series and parallel strings of low voltage battery cells. As the battery pack is charged and discharged as a unit, individual cell temperature and internal chemistry characteristics can cause capacity imbalances in the form of voltage variations. Imbalanced cell voltages are caused by differences in cell capacities, internal resistance, chemical degradation, and inter-cell and ambient temperature during charging and discharging. Any capacity imbalance between the modules can threaten the long-term stability of the string as overall pack capacity is brought to the upper and lower limits of charge. Imbalanced cell voltages can cause cell overcharging and discharging, and decrease the total storage capacity and lifetime of the battery.

Given similar battery modules, one can attempt similar cycle-induced aging by making sure the voltages of each battery in series are matched to the others. For battery technologies used today, voltage plays a large part in determining state of charge of the battery. Different solutions for controlling battery state of charge have been proposed in the literature [1]-[5].

Passive methods for controlling battery state of charge vary between chemistries. Lead-acid batteries are capable of limited equalization by extended charging. While the lower cells in the batteries continue to charge, the batteries with the highest state of charge are forcibly overcharged. Equalization is attained in lead-acid batteries due to the hydrolysis process during over-charging which slows the flow of charge to the batteries with the higher states of charge while allowing the lower states to continue at the normal rate. This cannot be repeated forever without eventual damage to the battery, where the side reactions and the loss of water degrade the performance and life of the unit. Such equalization methods are termed passive equalization. Not all chemistries are capable of such overcharging; lithium-ion batteries which are becoming more prevalent in large battery packs show immediate adverse effects to the practice. Externally-aided passive equalization includes resistive shunting, where charging current is drawn off the highest voltage battery through a shunt resistor, lowering its voltage to a safe level. Such passive equalization wastes energy, while today's high-efficiency vehicles strive to conserve every last watt. Active equalization uses external circuitry to shuttle charge or balance voltages between battery cells whether in charging or discharging, keeping the voltages within their safe limits without dissipating precious energy.

One method to balance series-connected batteries is to use a capacitor directly connected alternately between both batteries to shuttle charge from a battery with a higher state of charge to one with a lower state of charge [1] as shown in Fig. 1.

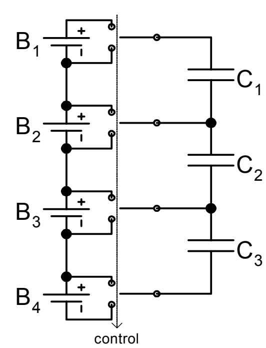

Fig. 1. Direct-connect method

Another capacitive balancing method, based on the Cük converter, has been proposed as well [2]. The Cük converter uses capacitive energy transfer, same as the last method as shown in Fig. 2. The cell voltages would be read by a micro-processor-based battery management system; rate of equalization would be determined by altering the pulse width modulation signals for the switching electronics. Each dc-to-dc converter would straddle two adjacent batteries and allow charge transfer between them in either charging or discharging modes, similar to the last approach.

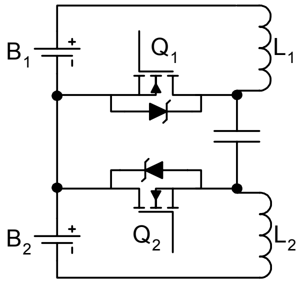

Fig. 2. Cük converter

An alternative to using a capacitor as a charge-shuttling device is using coupled inductors to provide electrical isolation from the series voltage stack while providing energy at any given point [3]. The coupled inductors would be instantiated in the form of a multi-winding transformer with capacitive outputs, shown in Fig. 3. Ideally, when identically wound the same voltage would be produced over all outputs, enabling any battery in the series stack to be charged to the same potential. This balancer is able to equalize batteries by charging them while the pack is in either charge or discharge modes.

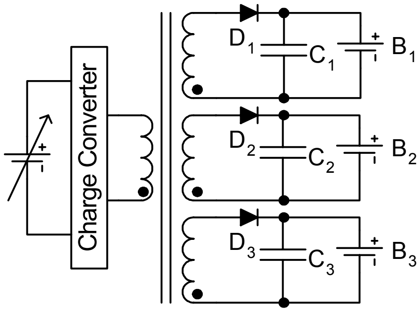

Fig. 3. Multi-winding transformer

Transferring charge between batteries can also be accomplished with a 2-battery buck-boost converter. This topology stores charge in the inductor connected to the intersection between the two batteries to be equalized, as shown in Fig. 4. This topology achieves an inverted output, which is compatible with a battery connected in series beneath it, similar to the capacitive shuttling method.

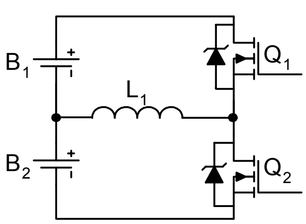

Fig. 4. Buck-boost converter

A circuit has been presented [4] that uses zero current switching to reduce switching losses and current stress of the MOSFETs, as well as reducing EMI emissions, as well as other buck-boost converters [5] which focus on the least amount of necessary parts per module instead of power quality.

In this paper a new topology of capacitor charge shuttling shall be presented. Bridging existing shuttling capacitors with additional capacitors can improve equalization speed of simple capacitive shuttling systems many-fold. Dynamic equalization using capacitors can take place whether the pack is charging or discharging, and can be implemented onto existing hardware. Improvements over the existing one-tiered method shall be shown and simulation results given.

II. EXISTING SINGLE-TIERED METHOD

In its simplest form, a charge balancing method would entail a capacitor used to shift charge among adjacent batteries in a string by first connecting to one of the batteries, then the other [1]. See Fig. 5 for an example of such a method in the form referred to later as a single-tier. Rate of charge equalization between any two batteries will be determined by switching frequency and balancing capacitor value, along with other factors such as parasitic losses specific to the particular topology. Inherent with the capacitive shuttling method is the ability to balance the voltage level of batteries in any state of charge and while the battery pack is either charging or discharging. If the time it takes to shuttle a unit of charge from one battery to the next can be expressed as time T, then the time it takes to shuttle charge from one end of the battery pack to the other is on the order of (N-1)*T, where N is the number of series elements in the pack. The method described does not use passive elements to smooth out current spikes during the transient off-on state and needs no controller circuitry which would change the frequency or order of switching. This would save complexity and weight if ripple-free operation was not required and conducted electromagnetic interference was not a concern.

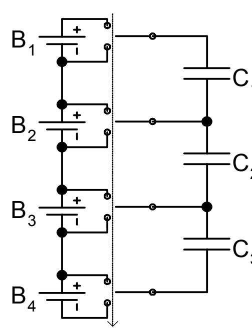

Fig. 5. Single-tier capacitor shuttling

In this method, switches shuttle charge back and forth in unison between batteries at a fixed frequency without regard to state of charge. The advantages of this system are that no sensing or closed-loop control is needed and the process is self-limiting: when voltage equalization is complete, the switching of the capacitors consumes minimal energy. The switching logic is shown in Fig. 6 for the blind switching pattern. For almost half the equalization time, the capacitors are connected to the battery higher in the series string, then after a short non-connected dead-time to prevent shoot-through, the capacitors are connected to the lower batteries. With the proper component ratings, one could use the same setup on multiple battery chemistries with no changes, as the system would tend to draw adjacent battery voltages closer together, not further apart.

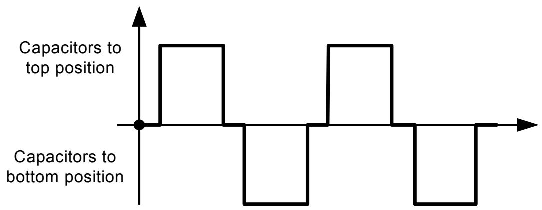

Fig. 6. Battery switching logic

III. New Double-Tiered Method

Fig. 7 shows the proposed method. In this method, by adding a new tier of capacitors in parallel with the existing capacitors as shown, not only are the adjacent batteries able to exchange charge as with previous methods, but other batteries not directly connected to one another can exchange charge as well through the bridging capacitors. One metric in comparing balancing systems is by how fast they can decrease voltage imbalances in their batteries. Drawing upon Fig. 5, the topology in Fig. 7 was created. Capacitors C_5, C_6, and C_7 act to provide a shortcut for charge flowing from battery to battery. Instead of the two switching cycles required to shuttle charge from B_1 to B_2, and then from B_2 to B_3 as in Fig. 5, the circuit shown in Fig. 7 provides an alternate path between the top battery B_1 and B_3 (through C_5). This new method requires only one switching cycle to transfer the charge between B_1 and B_3; hence speeds the transfer of charge between batteries.

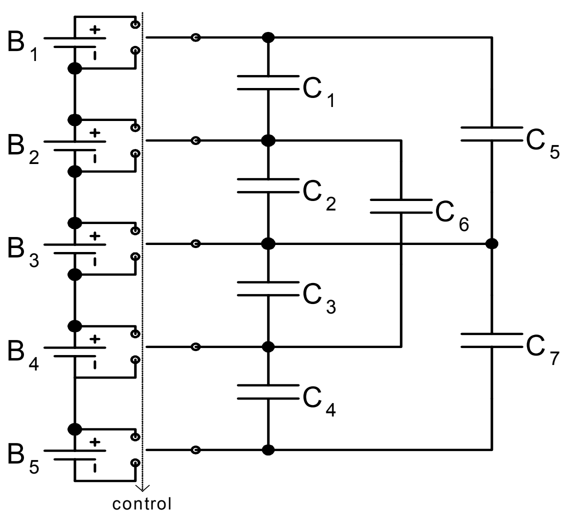

Fig. 7. Double-tiered balancing method

The balancing circuit was simulated in PSPICE using ideal capacitors with series resistances of 0.01Ω, and voltage-controlled switches with resistance min and max as 0.1Ω and 1 GΩ respectively, with a dead-time of a fraction of a microsecond. The batteries were portrayed as capacitors with values of 100µF with no equivalent series resistance. The balancing capacitor values ranged from 0 to 5µF and the switching frequency was 20 kHz. Balancing time was defined as the time required for a battery's voltage to breach 90% of the difference between its initial and final values. The absolute accuracy of this time is altered by the fact that balancing capacitors with substantial capacity relative to the batteries they balance will affect the batteries' voltages upon initial charge-up. In practical use any balancing capacitors will have drastically smaller capacities than the batteries they balance; this problem will be mitigated by comparing the ratio of the balancing times for the double-tiered topology versus the single-tiered topology. For this reason, improvements over the original design are shown with respect to the initial single-tiered reference case.

The doubled-tiered setup as it stands in Fig. 7 was instantiated using five batteries, whose initial conditions were 3V, 3.3V, 3.6V, 3.9V, and 4.2V, providing a sample spacing of voltages spread throughout the acceptable range of lithium-ion battery chemistry. The simulations ran until the system had stabilized; simulations were run for various combinations of tier one and tier two capacitances from 0 to 5 µF with the same initial voltage conditions and their balancing times recorded. Additionally, a select set of scenarios were also simulated to gather power loss data from the new balancing topology for comparison.

IV. Simulation Results

Fig. 8 shows the effect of adding a second tier of capacitance to the balancing system. Increasing the capacitance of either tier decreases balancing time. With no capacitance in tier two (simulating a single tier), doubling the capacitance of tier one approximately halves the required balancing time. However, as capacitance in tier two increases, increases in tier one exhibit diminishing returns in balancing time. With no capacitance in tier two, balancing time changes from 31 ms to 16 ms when the tier one capacitance changes from 1 µF to 2 µF, whereas a tier two capacitance at 1 µF decreased balance times by only a quarter with the same doubling of tier one. Given a certain desired balance time, the results of the simulation show several possible capacitor value combinations. This would allow the user to be quite flexible in picking capacitor values with a particular design limitation.

A comparison of resistive energy loss between the single and double-tiered method was conducted for a select group of tier capacitance values, as shown in Fig. 9. The power loss across the equivalent series resistances for all of the balancing capacitors was summed over the balancing time to get total energy loss. The power loss across the switches was not part of the total power loss equations; switch implementation and characteristics are not within the scope of this paper. The general trend of energy loss is to decrease with increased tier one capacitance. With no tier two capacitance, there is a highpoint of energy losses at 1 to 1.5 µF. With 1 µF of tier two capacitance there is a sharp drop in power dissipation between 0 and 0.5 µF of tier one capacitance and a slight upward trend from then onward. With 2 µF of tier two capacitance the losses level off after reaching the tier one

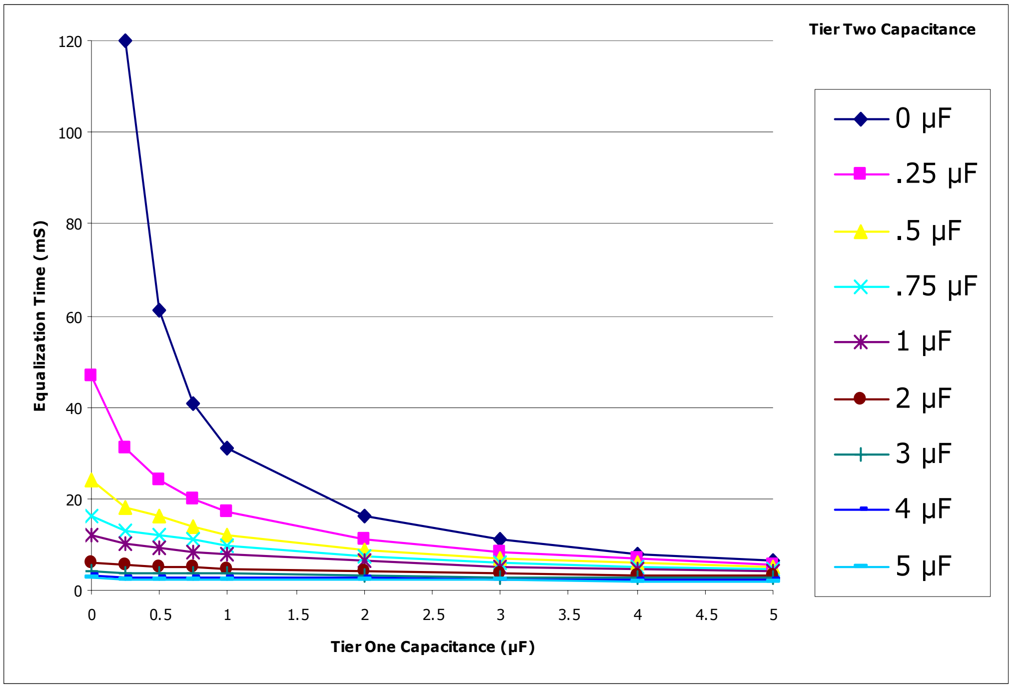

Fig. 8. Equalization time results of double-tiered scheme vs. tier capacitance

1 µF mark. From this data one can infer that adding a second tier of capacitance can substantially decrease energy losses in the system and that beyond a certain point, increasing the size of the tier capacitances results in diminishing returns in energy losses. The loss is reduced for the same reason there is less equalization time; a shorter path for charge to follow while balancing the series string of batteries. This is fortunate, as the results point to the ability to increase capacitance and decrease equalization time while not substantially impacting the efficiency of the balancing system.

V. Practical Applications

In some applications, the amount of capacitance used in balancing may be limited by available space, as for a given voltage rating a higher capacitance can translate into a larger package. In this instance there is a choice between a few large capacitors or several smaller ones, assuming one can fill the available volume with the new components effectively; according to simulation results it is more advantageous the distribute the capacitance equally among the two tiers rather than lumped in one tier. This yields a 50% decrease of balancing time. 8 µF of total capacitance in the form of tier one capacitance of 2 µF each and tier two set to 0 µF takes 16 ms to equalize the system, whereas 7 µF in the form of 1 µF for each capacitor in tier one and 1 µF for each in tier two required only 6 ms, showing that for nearly the same bulk capacitance there can be a decrease of balancing time of approximately 50% by applying the new equalization topology.

Another approach to increased speed of equalization is to simply use the same capacitor values in tier two as initially used in tier one. This change would yield nearly a four-fold decrease in balancing time over a single-tiered

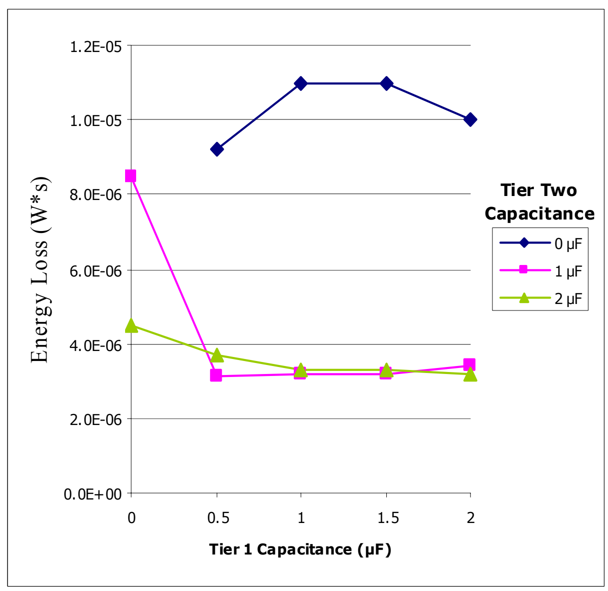

Fig. 9. Energy loss vs. tier 1 capacitance

approach with the same capacitor value. As shown in Fig. 8, with tier one as 1 µF and tier two as zero, a 31 ms balance time results. When both tier one and tier two are 1 µF, an 8 ms equalization time results, a time 25% of the original.

VI. Conclusion

Of critical importance to the auto industry are battery packs which keep their voltage profiles in a reliable manner. Since batteries are unreliable in the long-term, balancing circuitry must be used to ensure a balanced pack. A new topology of capacitive balancing was proposed and found to significantly decrease balancing time and energy loss with respect to an existing reference battery balancing technique. This new balancing topology is simple to implement or tack onto an existing design for decreased balancing time without significant modification to hardware.

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