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Optimal Control of Battery Energy Storage for Wind Farm Using Monotonic Charging/Discharging Strategy

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ABSTRACT: Rechargeable batteries are widely applied in portable devices, electric vehicles, hybrid electric vehicles, energy storage systems, etc. To meet the load voltage requirements, the batteries are usually connected in series. Because of the manufacturing variance of cells, series-connected batteries without a proper balancing method suffers serious unbalanced problems, which lead to safety issues, shortened lifetime or decreased usable capacity. To improve the battery life and usage capacity a modified balancing method for series-connected batteries applications is proposed. The proposed method uses a transformer to couple the energy from charger or discharger to batteries for energy balancing. The proposed method has the advantages of high efficiency, compact size, suitable for any type of switching converter, load-related balancing energy, and extremely simple structure without any additional controls for voltage balance function. The proposed balancing method has the following advantages. It does not suffer from inrush current and is capable of SOC balancing since the coupled energy from charging or discharging current can be regarded as a current source. Additionally, the proposed method can be applied to any type of switching converter, making it suitable from low-power to high-power applications.

I. INTRODUCTION

The increasing use of lithium-based battery cells in electric and hybrid vehicles has presented many challenges in terms of system design and safe use of the cells. These challenges include the unique characteristics of the battery chemistry that requires new technologies for monitoring and maintaining the battery cells during use, real time decision making based on measured parameters, and optimizing the overall system to obtain the maximum performance .a single battery cell presents low nominal voltage (limited due to the active materials chemistry), battery cells are usually connected in series to be employed in many applications, such as electric vehicles (EV), hybrid electric vehicles(HEV), photovoltaic (PV) systems or telecommunication battery energy systems. Unbalanced cell voltage within a series string can be attributed to the differences inthe cell's internal resistance, unbalanced State-Of-Charge (SOC) between cells, degradation and the ambient temperature gradients during charging and discharging . Voltage monitoring and current diversion equalization circuits and Battery Management Systems (BMS) have been developed to prevent unbalances during charging and discharging in a series connected battery cells . This repeated charge and discharge phenomenon causes a cell mismatch problem because lithium-ion batteries have inevitable differences in chemical and electrical characteristics from manufacturing, and accelerate asymmetrical cell degradation with aging . The problem is that when these imbalanced batteries are left in use without any control, such as cell balancing, the energy storage capacity decreases severely, and in the worst case, there may be an explosion or fire. Lithium-ion batteries require careful management, particularly with regard to overcharge and undercharge problems. Thus, charge equalization for a series connected battery string is necessary to prevent these phenomena and extend the useful lifetime. Numerous charge balancing circuits have been presented and well summarized . They can be classified into two categories, dissipative and nondissipative. Example of dissipative balancing method could be based on shunt resistive method. It is the simplest and cheapest cell balancing. This method could be operated continuously on each cell independently but this method presents high energy losses, which reduces the energy efficiency.

Many balancing systems have been developed in order to equalize the charge among the different cells connected in series in battery packs, usually divided in passive or active balancing systems. Besides some assumptions related to the temperature and the series impedance, it can be stated that the lithium cell voltage is related to its state of charge, especially after a large relaxation time. As a result, equalizing voltages among cells connected in series is a good solution to equalize charge levels and to prevent any cell from operating outside its nominal charge levels.

The passive balancing solutions are dissipative techniques that operate only under charging conditions to equalize the charge level among the cells. Resistors are used to bypass apart of the charging current or even to discharge the cells already fully charged. The equalization times are long because this method operates under low bypass currents to limit the heat generation. The pack performances are determined by the weakest cell and the energy is wasted during the bypass balancing process. The active cell balancing techniques are based on the energy exchange among cells, equalizing the charge differences by taking energy from the most charged cells and transferring it to the less charged cells. The operation is possible and advantageous at any time or operating conditions.

The energy is not anymore entirely wasted during the equalizing process but is redistributed among the cells. If the active balancing system has been designed for large current ratings, it can also operate during the battery discharge to support the weakest elements of the battery. In such a way, charging or discharging the battery can be supported in real time with large transfer of capacity balancing devices, making possible the global energy stored in the cells to be accessed and furnished to the load.

The balancing of a lithium-based battery system has one very large benefit. As the batteries are charged and discharged their capacity is reduced. The unbalanced discharging and charging of cells accelerates the time before the cell capacity is diminished to the point of the system being no longer useful or decreases the time before failure. The equal charging and discharging of the individual cells allows the end user to obtain the maximum energy and life out of the battery system as a whole, eventually saving cost and environmental resources. While battery energy capacity, weight, and reduced harm to the environment are continually being improved, the technology is still slower progressing than the technology using the batteries as an energy source. Therefore, the utilization of the present battery technology is of great importance.

II. LITERATURE REVIEW

This section introduces the literature and the associated work that has been completed both recently as well as previous work. The overall goal of this chapter is to provide a basic understanding of the topic as well as describe the new direction to be taken during the research on the subject.

A battery management system is a system that monitors the cells in a series connected string for a number of variables. These variables can include individual battery voltage, state of charge, and total pack voltage. The BMS usually has protection mechanisms built in for over and under voltage situations, but can also include temperature sensing and failure modes of batteries. Some BMS designs will also incorporate a method of communicating data back to a central interface for the user to see or a computer for analysis later. Asumadu, Haque, Vogel and Willards (2005) show a design for a BMS with a very clear communications protocol to be transmitted back to a laptop or PC. An example of a general BMS system is shown in Karnjanapiboon, Jirasereeamornkul, and Monyakul (2009), where the cells are balanced through flyback DC-DC converters using a central controller. This system does not communicate back to a PC or other data logging device to aid the end user in troubleshooting or during general use of the battery pack. It also does not give an indication of whether or not a failure has occurred. More examples of general and more complex systems that range from the simple passive to complex active systems can be seen in Kutkut 6 and Divan (1996). The wide range of complexity in the circuits gives an idea of some of the challenges that will be encountered in the design process of a BMS for a larger battery system.

There are two types of BMSs that are commonly found in commercial and industrial lithium battery based systems. Each type of system has different benefits that vary among cost, efficiency, and complexity. The first style of BMS is a passive system. Battery stacks that are being produced today largely use a passive cell balancing method (Bonfiglio&Roessler, 2009). The passive system is more basic in the fact that it only operates during the charging cycle of the battery stack. Kutkut (1996) states a disadvantage of the passive system as: One drawback of this approach is that the recovered energy is converted into additional losses in shunt elements (p.1). The wasting of energy effectively leads to overall lower system efficiency, counterproductive to the idea behind electric vehicles. The second type of BMS is the active management system. The active management system is more complex than the passive system. It has the ability to be far more efficient in charging the cells while taking a shorter amount of time. It was stated that the difference in charging time of a 24V@60Ah battery was 6.4 hours for a balancing system versus 7.6 hours without the balancing circuit (Zheng& Zhao, 2009). Unlike the passive system where extra power is often wasted as heat, the energy is reused in the charging process. Active BMS schemes range from a switched capacitor topology as shown in (Baughman &Ferdowsi, 2008) to a flyback converter topology as shown in (Bonfiglio &Roessler, 2009). The two active BMS schemes that will be examined before the initial design process are the flyback converter and bi-directional DC linked bus, with the following figs showing the design for each. These schemes include:

The flyback converter (Bonfiglio&Roessler, 2009).

The bi-directional DC linked bus (Karnjanapiboon, et al. 2009)

An advantage of the fly back converter scheme, as shown in Fig 2.1, is the automatic nature of the balancing. When the primary of the transformer is being switched, the secondary with the lower cell voltage will naturally draw more current, receiving a charging current inversely proportional to the cells SOC (Moore & Schneider, 2001). This method of operation requires that all secondary switches are on while the primary is being switched. The other mode of operation is when only one secondary is used to provide a balancing current. The fly back converter balancing scheme allows for the use of just n+1 number of switches in the balancing circuits. However, as noted in (Moore & Schneider, 2001), this somewhat similar scheme requiring individual secondary windings for each battery cell is complex in design due to transformer construction and the switches. The maximum number of cells would be fixed as adding more secondary windings could not be easily added (Moore &Schneider, 2001).

III. METHODOLOGY

The balancing system is based on the well known buck–boost chopper The next-to-next elementary modules are implemented in such a way that the power can flow in either direction from one cell to the other. The staggering of the balancing units or modules creates a multi cell next to next balancing system. The elementary balancing module is composed of two transistors (bidirectional current flow and unidirectional voltage capability) and an inductor LN.

A balancing module is connected across two adjacent cells to allow next-to-next energy transfer from the cell with higher voltage (or higher state of charge) to the cell with lower voltage(or lower state of charge).The number of modules must be equal to the number of cells minus one. TN and TN- are activated with a pulse width modulation signal (PWM). By adjusting the duty cycle of this signal and/or considering the voltage differences between two adjacent cells, the current through LN can flow in either direction with the desired magnitude.

In addition, if the freewheeling operation is carried out by the body diode of the transistors, the converter is simple to drive but inefficient at these voltage ratings. The same converter architecture can be operated in continuous mode to reduce the storage and the filtering needs. In such a case, the control strategy of the converter must be developed in-order to keep the balancing current under a maximum level no matter what the operating conditions of the balancing module. As in discontinuous mode operation, two simple strategies can be used, either the converter is operated under fixed duty cycle or under maximum current clamping. In the first case, the converter duty cycle can be set to 0.5 and both transistors are driven. As a result, the balancing current flows naturally from the cell with the higher voltage to the cell with the lower voltage level.

The current can be continuous in the inductor and its level becomes dependent on the parasitic and the voltage mismatch between the two cells. Especially, the series resistors in the circuit such as the RDS on of the transistors are critical elements in the current ratings. In this case, the greater is the voltage mismatch between the two cells, the higher will be the balancing current.

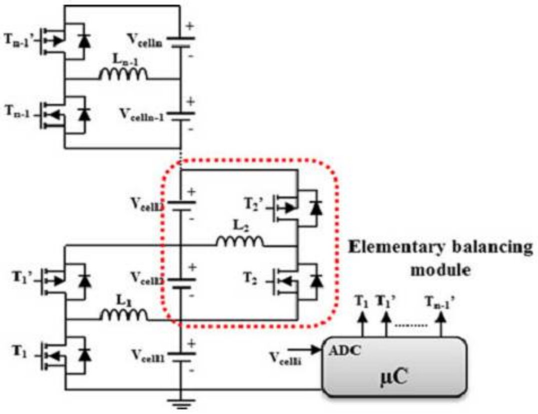

Fig.1 Basic topology and converter stacking

The elementary balancing module is composed of one P channel MOSFET, one N channel MOSFET, and an inductor. The MOSFETs are driven by a microcontroller, by applying on both gates the same PWM driving signals for complementary operation, for example 0.5 duty cycle. A special care must be taken to optimize the switching transitions of the complementary chopper to prevent the short circuit occurrences at each commutation. In this case, the energy is transferred naturally from one cell to the other. Operated under continuous current mode and making the assumption that the voltage unbalances remain within a maximum range, this topology is simple to control. It can offer high transfer current levels and improved efficiency because only MOSFET operation is allowed since they are operated in synchronous rectification mode, reducing the voltage drop across the diode and consequently the losses of the converter.

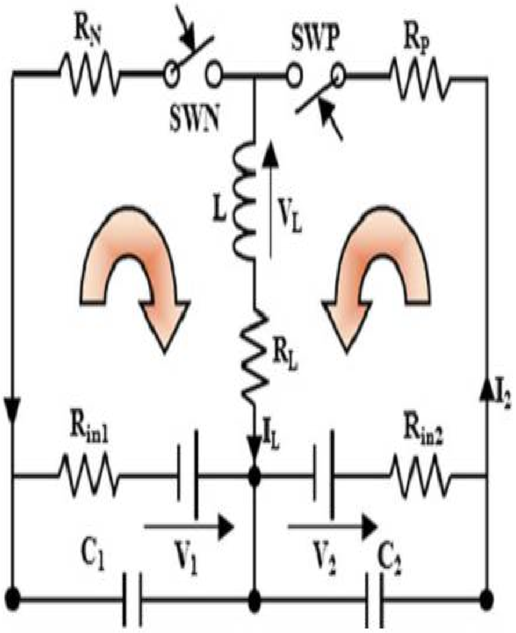

Fig.2 Equivalent Schematic Diagram

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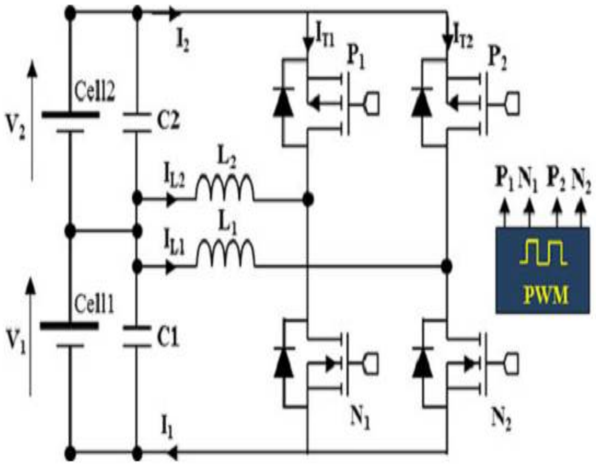

Fig. 3 ReducedCapacitor Filtering Needs

At first, we propose an improved topology that corresponds to a basic interleaved topology with two coils in parallel as shown in Fig and considering 180◦ phase shift angle driving orders between the two converter arms.A second coil with its own CMOS arm is added to the first topology. The switches $P1$ and $N1$ operate in synchronous rectification mode and the two arms are 180◦ phase shifted from each other. The two conversion units are interleaved under a duty cycle of ideally 0.5 but duty cycles close to 0.5 are also very favorable to increase the current levels. Therefore, the input and output currents of the cells are “the sum” of the currents flowing in both coils as it is represented in Fig as shown below.

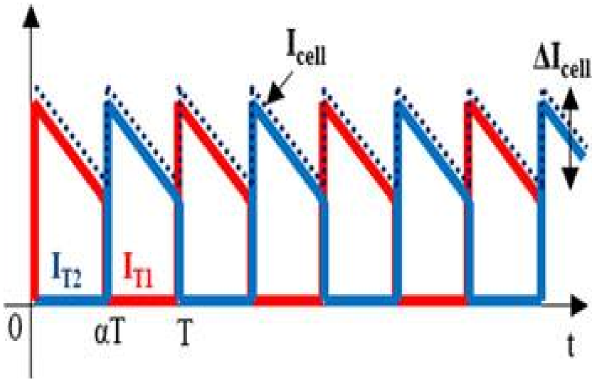

Fig. 4 Shape of one cell current with two interleaved conversion units for 0.5 duty cycle.

As it can be seen, the ripple current applied to the filtering caps is greatly reduced. Therefore, this approach allows reducing the filtering needs, and thus the size of the capacitors $C\ 1$ and $C\ 2$. The implementation of two converters in parallel will either double the balancing current level if both interleaved units are designed at initial design ratings. Otherwise, the design of each conversion unit will have to consider current ratings divided by a factor of two. In such way, the main limitation of this approach becomes clearly the increase of the number of the components, especially the active devices.

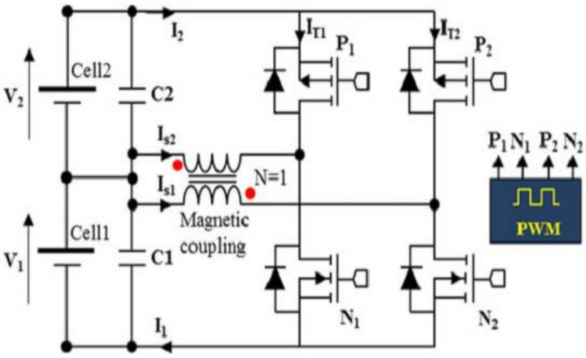

Fig.5 Downsizing the Coils

In order to improve the topology previously proposed, the two coils can be winded on the same iron core. This double-winded coil replaces the two discrete coils of the second topology, maximizing the com- pactness of the overall inductor. The currents flowing in the two windings have symmetrical dc levels. Therefore, the windings are connected in order to compensate the flux generated by each of them into the magnetic core.Almost perfect magnetic compensation is obtained, offering great size reductions of the magnetic device no matter the value of the duty cycle. If the converter is always operated under fixed 0.5 duty cycle, the coupled inductor can be optimized with a minimum leakage inductance. Nevertheless, it is also possible to operate the converter with coupled inductors under variable duty cycle, designing the magnetic device to exhibit the required leakage inductance. only small variations of the duty cycle are necessary to enlarge greatly the balancing current. As a result, the leak- age inductance needed to filter the coil currents remains very small. As an example, for a duty cycle variation of 10% above and below 0.5, the leakage inductance necessary to moderate the inductor current ripple to 0.5 A over a dc level of 5 A per coil is 6 μH which is a realistic value compared to the mag- netizing inductance value of 30 μH. It is this expected design and optimization result based on the fact that the application only requires small duty cycle variations around 0.5 and that the CMOS arms and their associated drivers can operate at high fre- quency and under very small duty cycle mismatch that evident the contribution of this work.

In addition, this third topology provides the same advantages as the second one, which is to ensure the continuity of the charge or discharge currents in the cells, thus reducing the size of the filtering capacity and increasing the balancing speed. Furthermore, the current compensation at the magnetic device level is an opportunity to manage short overcurrent levels in the balancing converters, which may simplify the implementation. Indeed, the magnetic flux level in the magnetic core has become independent from the average current flow in both windings. As function of the heat removal capabilities, the short converter overload is made possible without the immediate magnetic core saturation. The modeling and analysis of the topology with respect to the operation characteristics will be presented in the following section.

A) EQUIVALENT SCHEMATIC DIAGRAM

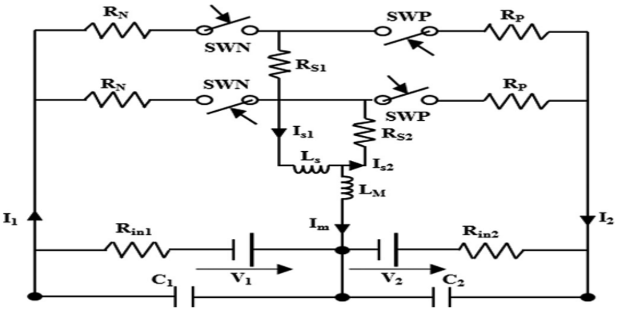

Fig. 6 Equivalent Schematic Diagram

IV. SIMULATION RESULTS

The simulation results presented in Fig are in accordance to those of the second topology, the flowing current being very regular. However, in this case, the design of the magnetic devices is greatly optimized. This improved next-to-next balancing system is smaller, more efficient, and easier to integrate. Fig shows a demonstrative result of the balancing operation applied to a pack of eight cells in se- ries with great voltage imbalances. The seven converters with coupled inductors are operated under natural control technique with fixed duty cycles all equal to 0.5. In this case, the system automatically finds the balanced point and sets the balancing currents in the good direction.

As far as the simulation of the eight cells pack is concerned, the battery cells are initially charged under various voltages from 2.8 up to 3.3 V with a total stored energy of 91.6 Wh. Initially, with one cell almost fully discharged, no energy can be delivered by the battery pack. After the balancing action, the mean voltage level accord of all the cells is 3.05 V and the total available energy is: 86.6 Wh. As it can be seen, over 5Wh have been lost, but about 86.6 Wh are now available and can be used to supply a charge with the battery. In the following section, the experimental work will demonstrate the interest of the converter and will validate our analysis. We will now present with more details what can be expected from the magnetic devices in terms of design and performances.

In order to validate the performances of the proposed converter a simulation model of the converters are designed in the MATLAB tool , The PWM generation and the converter modeling are been done using the MATLAB tool kit , which the results are being analyzed. For the balancing performance comparison between each structure, the simulations for six cells were carried out using MATLAB.

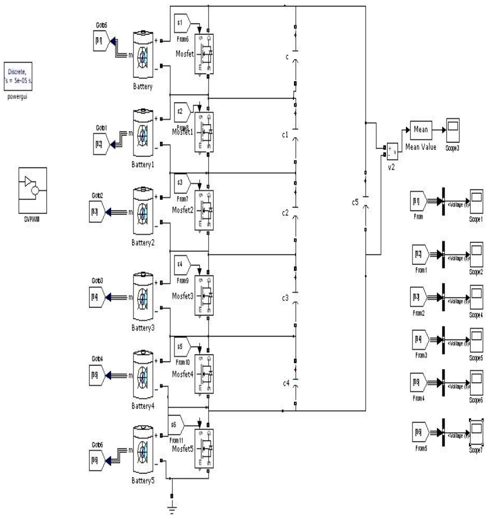

Fig.7The MATLAB simulation diagram of existing circuit

Fig.7 shows the MATLAB simulation diagram of existing circuit. The chain structure using the additional capacitor to reduce the burden of additional switches. The additional capacitor is tied to series-connected capacitors.

An optimized Topology for Next-to-Next Balancing of Series-Connected Lithium-ion Cells is simulated to verify the operation, which are presented in the wave forms below , and the paramerters used for the simulation are listed below.

The battery cells are modeled to represent the nonlinear electrical charge characteristic versus the voltage level behavior of a regular battery. The simulation parameters are:

1. voltages of the two cells: $V1 = 3.3$ V, $V2 = 2.8$ V, $Rin1 = Rin2 = 10$ mΩ;
2. inductance coil $L = 30$ μH, $RL = 10$ mΩ;
3. switching frequency $Fd = 100$ kHz;
4. MOSFETs P,N with low Rds (20 mΩ);
5. schottky diodes D1 and D2.

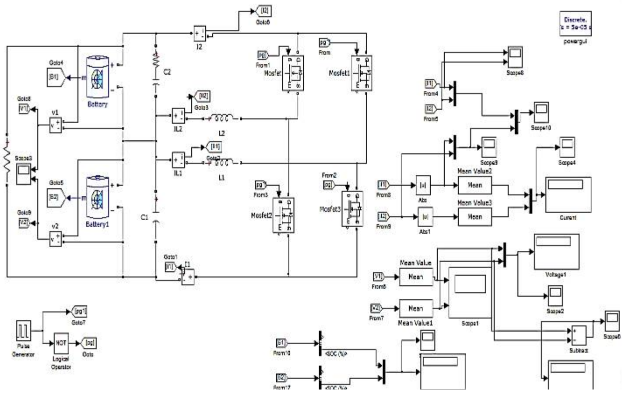

Fig.8The MATLAB simulation diagram of proposed circuit

Fig. 8 shows the MATLAB simulation diagram of proposed circuit. An improved topology is proposed which corresponds to a basic interleaved topology with two coils in parallel as shown in Fig. 5.8 And considering 180◦ phase shift angle driving orders between the two converter arms.

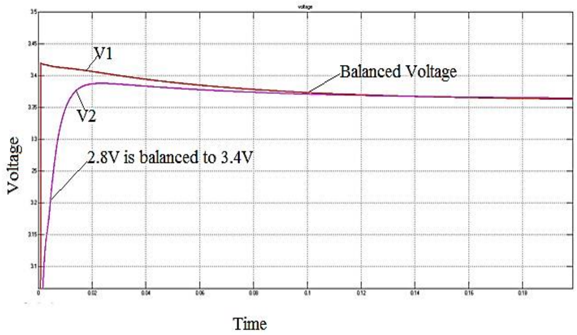

Fig. 9 Simulation of the two cells pack

Fig. 9 As far as the simulation of the two cells pack is concerned, the battery cells are initially charged under various voltages from 2.8 V up to 3.4 V.

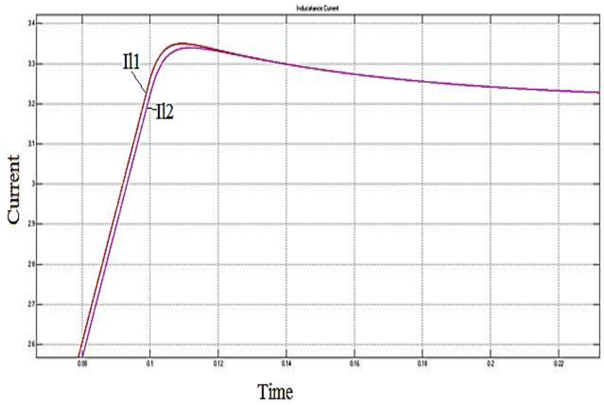

Fig. 10 The inductance current

Fig 10 shows the inductance current. For the operation of the converter at the switching period scale, it can be seen on Fig. that the currents within the two coils are very comparable with less than 0.1-A mismatch without regulation needs.

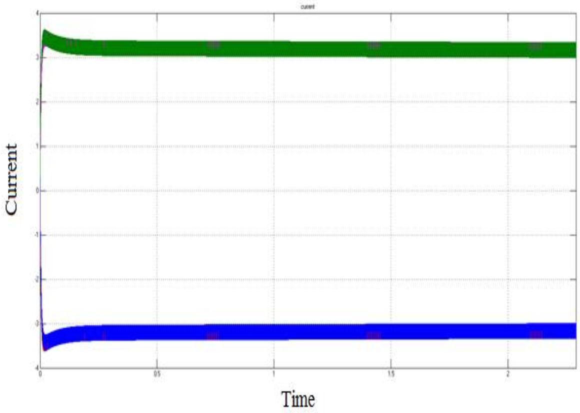

Fig.11 The current in the coil in the case of natural balancing

Fig.11 represents the current in the coil in the case of natural balancing whereas X denotes the time in secs and Y denotes the current in Amps.

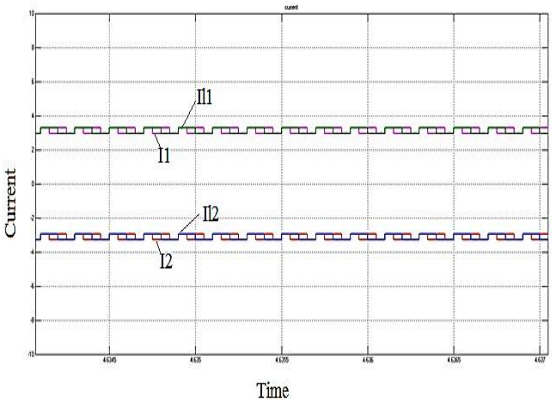

Fig. 12 Current in the coil

Fig12 is plot between time in X-axis and current in Y-axis, which are in accordance to those of the proposed topology, the flowing current being very regular. However, in this case, the design of the magnetic devices is greatly optimized.

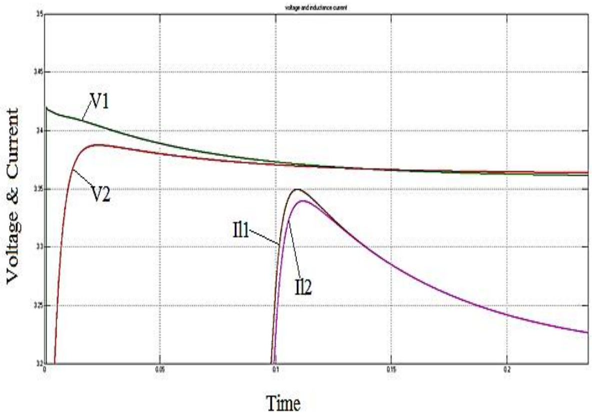

Fig. 13 Cell voltage and current in the coil

Fig.13 represents the Cell voltage and current in the coil where X-axis represents the time in secs and Y-axis represents the voltage in V & Current in Amps.

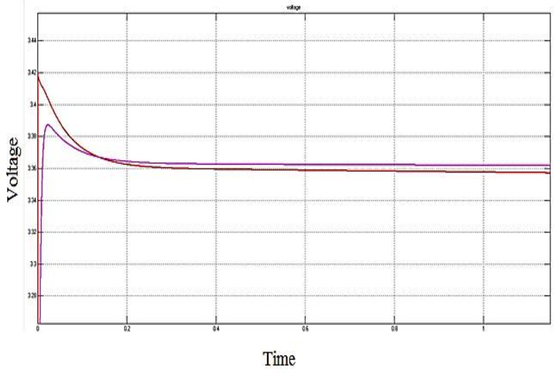

Fig. 14 Time domain response

Fig. 14 shows the time domain response while operated under fixed 0.5 duty cycle and with an initial voltage mismatch of 0.24 V. It can be seen that the voltage mismatch has been reduced below 50 mV which is usually the accuracy range of the BMS voltage monitoring. Here X-axis represents the Time in secs and Y-axis represents the Voltage in V.

V. CONCLUSION

In lithium-ion batteries, the cell balancing speed of the switched capacitor based balancing schemes is been validated and the response of the balancer is slow when outer cells are n bounded and the balancing requires a longer time. To increase the cell balancing speed, this project proposes a chain structures of the switched capacitor. The proposed structures have a direct or indirect path for charge transfer between the uppermost cell and the undermost cell. In this project balancing strategy are been studied with the capacitor balancing ,the conventional half bridge balancing provides a better balancing compared to the capacitor structures as they require a longer time in balancing which makes them, unsuitable for higher number of cells, The proposed topology is been more effective and more compact topology that can meet the application requirements for integration, performance, and cost, addressing applications such as electric vehicles and smart grids.

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