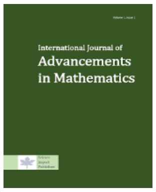

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An Efficient Hybrid Charge Balancing Algorithm for Plug-in Hybrid Electrical Vehicles

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Abstract

Batteries are the main source of fuel for Plug-in Hybrid Electric Vehicles (PHEVs) as number of cells are connected in series and parallel to produce sufficient power to drive the motor. In order to fully utilize the battery storage, Battery Management System (BMS) is employed in PHEVs. Efficiency of battery can be drastically decreased when there is charge mismatch between the cells or between cell modules. To balance the charge in cells, several techniques has been proposed. However, these techniques took long time to balance the charge or some are not cost effective. To these problems, this paper proposed a novel hybrid algorithm which utilizes two algorithm solve Double Tiered Shuttling Capacitor (DTSC) and resistor shuttling. When the SoC difference is greater than 4%, DTSC will take over the control as it has less power consumption for greater SoC difference and for less than 4%, resistive shuttling overcomes as it has less power dissipation for lower SoC difference. The proposed algorithm is first simulated on MATLAB Simulink and then implemented on hardware for four lithium ion batteries connected in series. The result shows that proposed algorithm is the best candidate for Electrical Vehicle (EV) and PHEV due to less power consumption and cost effectiveness.

Keywords: Charge balancing algorithms, internal combustion engines, PHEV, EV

I. INTRODUCTION

In automotive electronics industry, PHEVs are most dominant and popular technology due to several factors like reduced amount of emissions, reduction of conventional fuel consumption due to usage of batteries, regenerative braking and long driving range etc. Internal combustion engine are relatively less efficient compared to electric motors and can obtain maximum theoretical efficiency up to 35% (reference needed), and in practical implementation achieve an overall efficiency of around 20-25 %. As compared to an ICE (Internal combustion engine), an electric motor has efficiencies in the range of high 90%, which means that almost 90% of electrical energy is converted into mechanical energy to drive the electric motor[1]. In addition, no gear mechanism is needed resulting in further higher efficiencies. In PHEVs, individual cell with 3.6 volts are connected in parallel and series combination to increase the current and voltage levels. In addition to this, more than 100 lithium-ion cells are present in battery pack and when one of the cell in battery pack become aged, other cells have to bear the same load causes to shorten the lifetime of the battery [2]. Many power solution companies like ‘Johnson Controls’, LG and Samsung etc. providing battery packs with 345 volts terminal voltage, 41 Ah battery capacity and total energy of 14.4 kWh. These specifications of battery are sufficient to drive the motor of PHEVs .One of the key advantages of PHEVs is that power to recharge the batteries is generated during regenerative braking, which otherwise is lost as heat in regular vehicles. On major issue of regenerative breaking during high speed is that very high charging current is generated which flows towards the battery. During the driving of electric vehicle, battery is continuously discharged and the terminal voltage of the battery decrease, so accurate instrumentation and control is necessary to manage the discharge of the battery in such a way so as to maximize battery lifetime. The state of charge information of the battery is also displayed to the operator of the vehicle through proper dashboard instruments, enabling a more informed user, which studies have shown result in further energy savings. Maintaining the voltage of battery also plays a very important role in extending the lifetime of the battery. If the battery voltage increases up to a certain level, it may deteriorate the battery and in some cases causes it to explode [3]. On the other hand, if voltage levels fall below a certain threshold level, short circuit may result which tends to overheat the battery and eventual premature failure of whole battery pack [4]. Moreover, all the cells connected in series and parallel combination, are not of the same kind even though of the same manufacturer. Each cell has different internal resistance, or change during the normal lifetime of the battery, different storage capacity due to which difference in voltage level of whole battery pack occurs during charging and discharging process. During the charging cycle, the cell with the lower internal resistance will be charged before the rest of the cells. Similarly, in discharge cycle, cell with the lowest capacity will discharge first. With this scenario, complete battery capacity of battery pack cannot be utilized. So, all the cell’s voltage should be balanced in order to increase the life span of the battery. Many algorithms for cell balancing have been published in the literature, which are discussed in the next section. The most important drawback of most of the algorithms is the long-time taken for charge balancing. Cost is another issue, where although the balancing time is fast, however the converter design is expensive and complex [5]. To address these problems, a novel hybrid algorithm has been proposed in this paper which allows a fast balancing time and a reduction in complexity and cost of the controller as well. Section II gives the quick overview of pre-existing algorithms and Section III explains the proposed hybrid charge balancing algorithm developed by the authors of this paper. Subsequently, Section-IV and Section-V shows the results and conclusion.

II. CHARGE BALANCING ALGORITHMS

Many attempts have been made to increase the battery life by charge balancing either cell to cell, cell to battery pack or battery pack to pack. Two types of unbalancing occurs between the cells in battery pack. First, all the cell have the same capacity but different State of Charge (SoC). Secondly, all the cell have same SoC but different capacity. All these unbalancing conditions are catastrophic for battery health and it is more catastrophic when the SoC difference between highest and lowest cell is large. To remove this unbalancing, there are three cell balancing topologies used to balance the charge for series connected strings: passive balancing, active balancing and converter based current balancing which eventually reduces the balancing time. However, such methods involves expensive elements like transformers, so they are relatively of high cost magnetic losses of transformer give rise to power dissipation while balancing the charge between cells [6]. Fig.1 represent some of the cell balancing methods and details of methods can be found in [7].

III. PROPOSED ALGORITHM

Many battery parameters like manufacturing parameters of battery, different discharge rate of individual cell, different capacity of each cell and difference in age of each cell contributes to the charge unbalance in the cell. In addition to this, charge level imbalance can be categorized in two categories, i.e. internal and external cell imbalances sources. Internal cell imbalance is due to the difference in the battery parameters and external cell balance arises due to the thermal characteristics of the battery pack and electronic

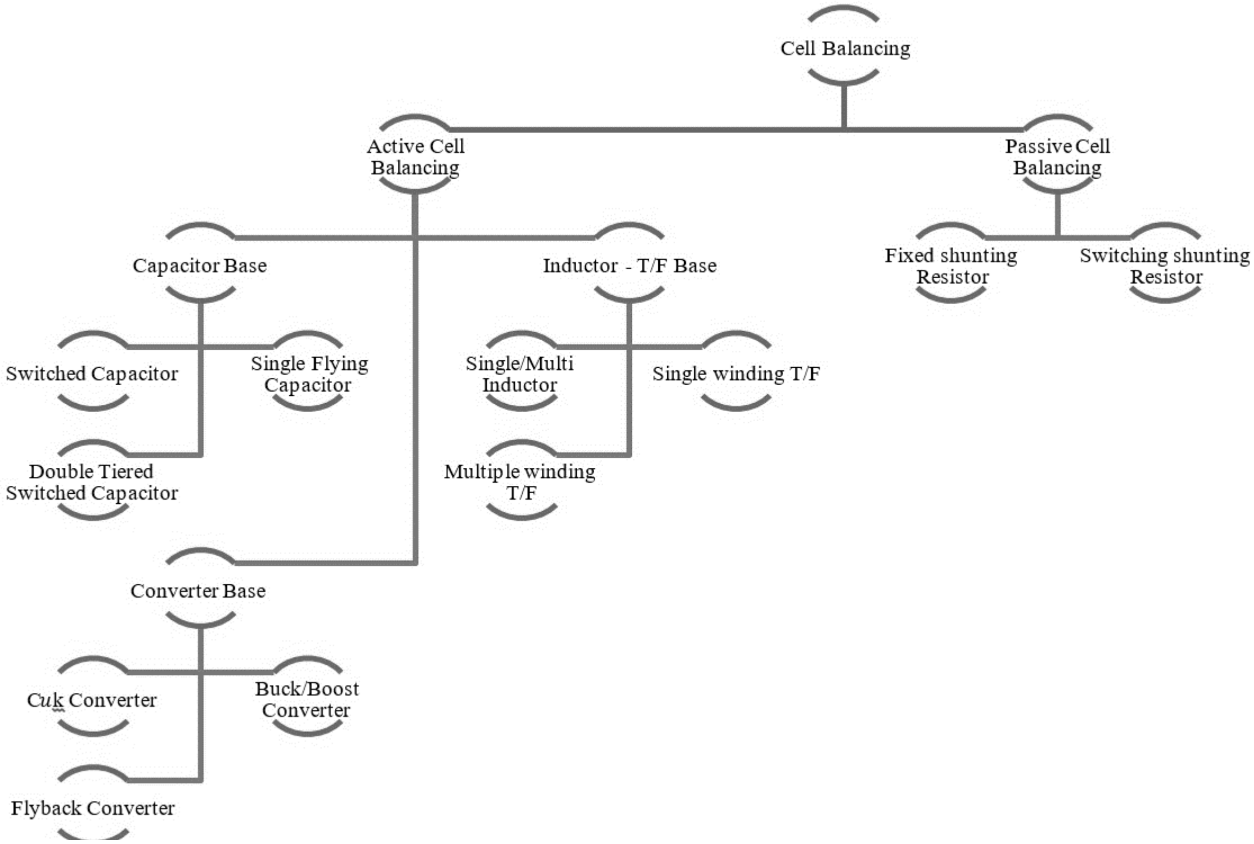

Figure 1: Active and Passive Balancing Topologies

circuitry used to protect the battery pack. Although, several techniques have been proposed to minimize the SoC difference between the cells, however, there is a strong contradiction regarding when to choose which cell balancing topology. Because, some of the cell balancing topologies, converter base cell balancing topologies, are very efficient in charge balancing as they provide high current density which minimizes the balancing time, but they are not cost effective. On the other side, the topologies which are cost effective either have poor charge balancing or take long time to balance their charge. So there is no single answer fit for all scenarios. To address these problems, a novel hybrid algorithm has been proposed which employs two balancing topologies. One from passive balancing, resistor shuttling method, and other from active balancing, double tiered capacitive shuttling (DTCS) method. The reason why double tiered capacitive shuttling method is used is that it has low balancing time when SoC difference is large due to extra capacitor added in parallel which minimizes the balancing time to half as compared to single tiered charge shuttling method and for less SoC difference, extra energy is dissipated through resistor. Ultimately, two algorithms worked together until 100% balancing was reached for all cells. When the SoC difference is above 4%, DTSC becomes active and starts transferring the energy from higher SoC cell to lower SoC cell. When the SoC difference reaches to 4%, resistor shuttling method takes over the control and makes the cells SoC to the lowest SoC cell in the battery pack by dissipating the extra amount of energy through the resistor.

A. Double Tiered Capacitive Shuttling Method

Capacitive shuttling method can be categorized in to three shuttling methodologies: First, basic switched capacitor, $n-1$ capacitors DTCS method is derived from single tiered capacitive method in which each cell has its own capacitor to shuttle the charge. The disadvantage of single tiered capacitor is that it can only transfer the charge to adjacent cell. By adding extra capacitors in parallel with existing capacitor as shown in Fig. 4, not only reduces the charging time to half but also charge can be transferred to alternate cell through one capacitor [8]. Another unit which can be used to compute the efficiency of DTSC and other balancing topologies is charge transfer per cycle i.e. how much charge is transferred in one cycle for a certain frequency. The charge transferred from one cell to other is carried out through the capacitor tiers. More paths means more tiers has been added to the circuit that causes less impedance to transfer the charge across the battery pack [9]. A MATLAB Simulink model is used to implement this active balancing technique with different capacitor rating. Each battery is modeled using two time constant (two RC equivalent model) to capture the dynamic effects. A voltage sensor is used to sense the voltage across each cell. SoC read from the cells equivalent model send the data to MATLAB function.

MATLAB function reads the SoCs of all the cells and operates the corresponding switches as:-

1. Compute the cell with the highest and lowest SoC. In the simulation cells are initialized with the following SoC (descending order) Cell4, Cell3, Cell2, and Cell1.
2. Transfer the charge from higher SoC cell to lower SoC cell, i.e. transfer the charge from Cell1 to Cell3 and Cell2 to Cell4 through C4 and C5 respectively. This will transfer the charge in one cycle.
3. If the cells with the high and low SoC are adjacent, then the charge will be transferred using C1, C2 and C3.

4. Jump to step 1 and continue until the SoC difference between highest and lowest cell becomes equal to 4%.

All the above mentioned steps can be implemented in MATLAB to compute the time taken to balance the charge between the cells. The switching logic of the capacitors is shown in Fig. 2.

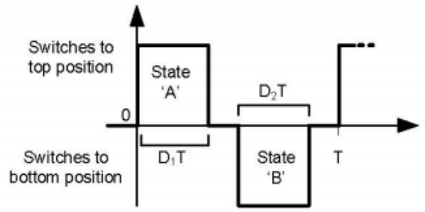

Figure 2: Switching logic for Capacitor (D1 = D2)

In the DTSC, SPDT switches are used which are switched for almost half time to up position and rest of the time to bottom position. There is a short relax time between these two switching techniques in order to avoid shoot-through.

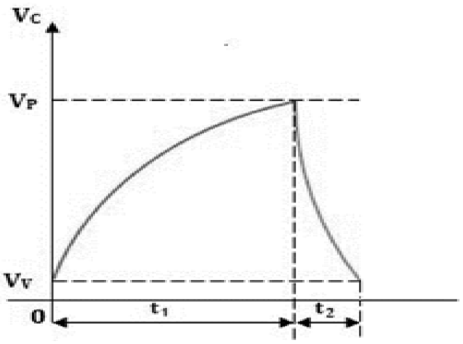

Figure 3: Voltage Swing of Capacitor during Charging

Where, t_1 is the time during D_1T (Fig. 2) and t_2 is the time during D_2T (Fig. 2).

Four cells each 2000mAh capacity are connected in series and parallel to capacitors. Initially, all the cells are initialized with different SoC (0.89) 89%, (0.86) 86%, (0.80) 80% and (0.74) 74%. SoC difference between adjacent cells are 2%, 7% and 2%. The highest SoC difference is 15%, 1.2 Ah. For the DTCS, cells are considered balanced if the SoC difference is 4%. The balancing algorithm of DTSC is shown in Fig. 4 [10]. The DTSC enjoys all the advantages of single tiered capacitor. In addition to this, the balancing time is reduced to half and this topology can work in both charging and discharging cycle. The maximum amount of energy that can be transferred using the DTSC can be calculated as: -

$$E = \frac{1}{2}C(V_H^2 - V_l^2) \qquad (1)$$

Where, V_H and V_L are voltage level of high SoC cell and low SoC cell respectively, and C is the capacitor which is used to transfer the change between V_H and V_L.

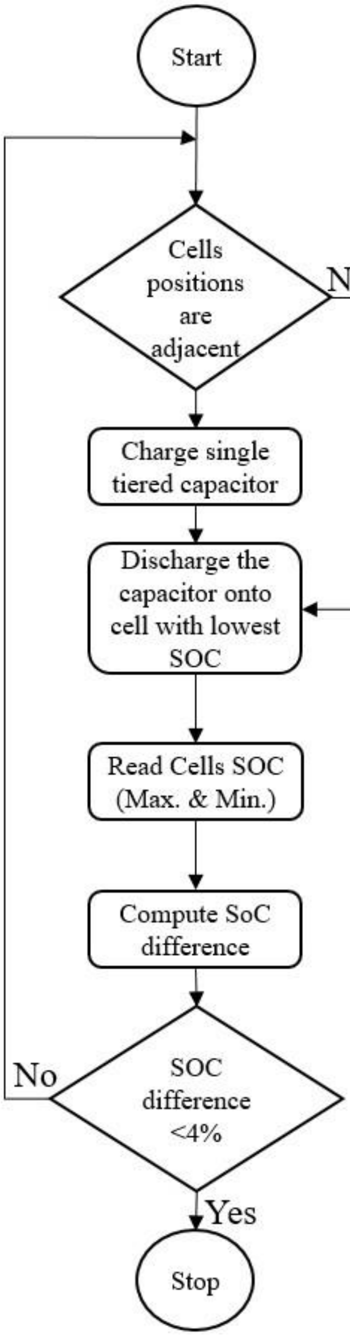

Figure 4: Double Tiered Capacitive Shuttling Method

And energy relation with the change in SoC can be calculated as: -

$$E \approx (\Delta SoC) Q\, V_{nominal} \quad (2)$$

And, $V_{nominal}$ is the average of high and low voltage,

$$V_{nominal} = \frac{V_H + V_L}{2}$$

Equation 1 and 2 can be compared as: -

$$\frac{1}{2}C(V_H^2 - V_l^2) \approx (\Delta SoC)Q\,V_{nominal}$$

$$\frac{1}{2}C(V_H + V_L)(V_H - V_L) \approx (\Delta SoC)Q\,\frac{V_H + V_L}{2}$$

By simplifying,

$$\Delta SoC \approx \frac{C}{Q}\,\Delta V \qquad (3)$$

Eq. 3 gives the relation of change in SoC w.r.t change in voltage where Q (charge) is in Coulombs.

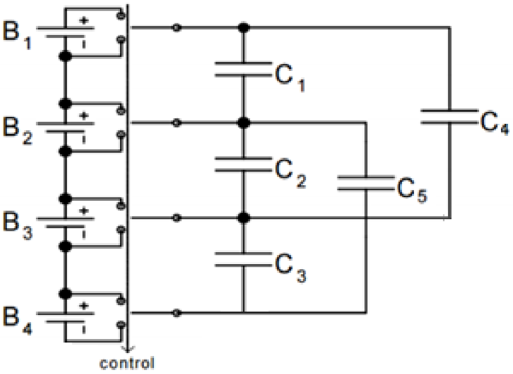

Figure 5: Double Tiered Capacitive Shuttling Method

The method described in Fig. 5 not only used to balance the charge in consecutive position of cells but also for alternative positions via only one capacitor. However, if the charge has be to transfer from one module to other module, an extra capacitor added between two circuits of battery equalization [11-13]. Such type of method is called modularization.

B. Resistor Shuttling Charge Balancing Method

In passive balancing, extra amount of energy is drawn out from the cells and dissipated through the resistor. Each cell has its own resistor and switch (either SPDT or Metal Oxide Field Effect Transistor (MOSFET)). The sensor sense the lowest SoC of the cell and turns on all the switches except the cell with the lowest SoC. Extra amount of energy from the cells dissipated through resistor until all the cells have SoC equal to the lowest SoC of cell. This process is shown in Fig. 6. This type of passive balancing is preferred because the charge is not continuously dissipating but in a controlled manner using switches or relays as shown in Fig. 7. In addition to this, this type of method further can be operated in two ways: First, by applying same on/off signal to all relays called continuous mode. Secondly, cells voltages are continuously monitored and when cell imbalance condition detected it decides whether the resistor should be shunted or not. This type of method is more convenient, simple, reliable and efficient as compared to previous one which makes it suitable candidate for Lithium-ion batteries. Figure 6 shows the balancing flow chart of resistive shuttling method. The value of resistor which can be used to discharge the energy can be calculated as: -

$$R_{Discharge} = \frac{R_1 + R_{SW}}{R_1 + R_{SW} + R_{load}} \times R_{load} \quad (4)$$

Where, $R_{Discharge}$ is the equivalent resistance across corresponding resistance, R_{load} is the load connected to the battery, i.e. motor and R_{SW} is the ON resistance of the switch or MOSFET. For hardware, Panasonic cells with parameters mentioned in Table 1 and Table 2 are used. By using those parameters, power dissipation can be calculated as [14].

$$P_{disp} = \Delta VI \quad (5)$$

Where, V is the change in voltage, i.e. before start balancing and at the end of balancing and I is the current which flow through the resistor while balancing.

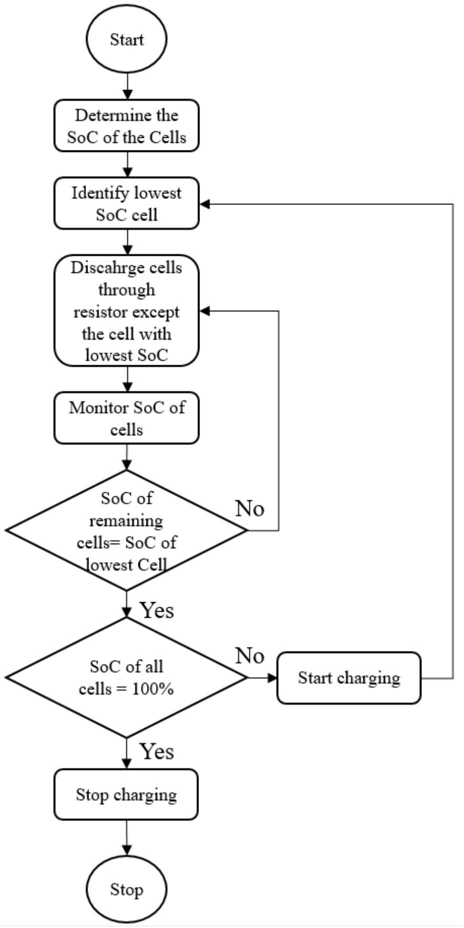

Figure 6: Functional Block Flow Chart of Passive Balancing (Resistor Shuttling Topology)

The resistor shuttling topology can be implemented in MATLAB using the following steps: -

1. Compute SoC of all the cells
2. Detect the cell with the lowest SoC

3. Turn on all the switches except the cell with the lowest SoC. This allows to dissipate the energy higher than the lowest SoC of cell through resistor.
4. Jump to step 1

The process will continue until all the cells will have the SoC equal to the lowest SoC of cell.

C. Proposed Hybrid Charge Balancing Algorithm (HCBA)

The hybrid charge balancing algorithm (HCBA) is combined model of resistive shuttling methods and DTSC. These two topologies work together to achieve the optimum charge balancing time and maximum capacity of the battery that can be utilized after balancing.

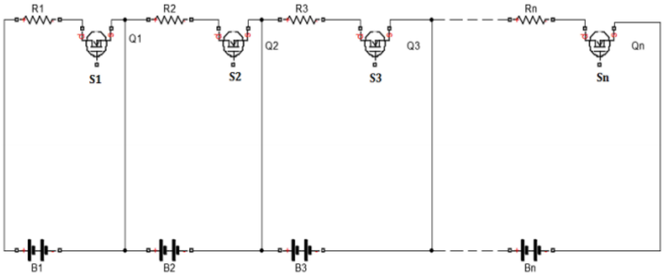

Figure 7: Resistor Shuttling Methodology

The HCBA enjoys all the advantages of DTSC and resistive shuttling balancing method. The working topology of the two algorithm is same as two of its individual components, and in the proposed algorithm, they are linked together i.e. each topology has to activate and start doing its job (charge balancing) when the SoC difference reaches a threshold value which is 4%. If the SoC difference between the cell having highest SoC and lowest SoC is greater than 4%, DTSC will start doing the balancing and when the SoC difference drop to 4% or less, resistive shuttling balancing topology will take over the control. The reason for choosing the 4% as threshold point is that at 4%, all the cells are said to be balanced when DTSC is individually balancing the charge. In this way, the whole capacity of the battery cannot be utilized because the SoC difference still exit. Using passive balancing to remove this difference allows the utilization of maximum capacity of the battery. The working methodology of HCBA is shown in Fig. 8.

The HCBA can be summarized in the following steps: -

1. Read the SoC of all the cells using the voltage sensor
2. Computer the SoC difference (Max cell SoC Min. cell SoC)
3. The difference computed in step 2 will determine that which cell topology should be turned on. If the SoC difference is greater than 4%, DTSC will be turned on
4. else if SoC difference is less than or equals to 4%, resistive shuttling cell balancing topology will be turned on.
5. Go to step 1

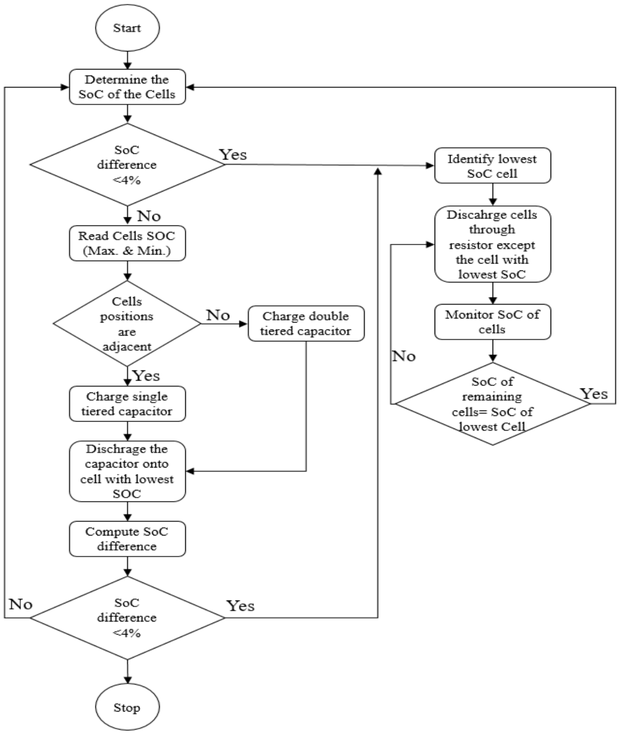

Figure 8: Functional Flow Chart of HCBA

The process will continue until all the cells will have the SoC equal to the lowest SoC of cell. In addition to this, the algorithm also has functionality to avoid the overcharge of each cell. This algorithm is first implemented on MATLAB using the four series connected Panasonic NCR18650 lithium-ion cells with the parameters shown in Table 2 and then implemented on hardware to check the stability of system. However, Table 1 represents the initial characterizes for the newly cells.

The switching frequency is 200 Hz with the duty cycle 45%. But these switches can be replaced with MOSFETs to further decrease the balancing time for fast switching. From Fig. 11, it is clear that to reach at 4% balancing level, it takes 1.7 hours (6120 seconds) that is half time as compared to single switched capacitor balancing topology.

Table I

Parameters	**Value**
Nominal Voltage (NV)	3.6 V
Rated Capacity	2700
Fully Charged Voltage	4.423 V
Capacity at NV	2440 mAh
Nominal Discharge Current	1.1739 A

Table II

	Initial Voltage (V)	**Capacitance (F)**	**Internal Resistance**
Cell 1	4.01	35	5mΩ
Cell 2	3.99	37	7mΩ
Cell 3	3.94	36	4mΩ
Cell4	3.88	34	6 mΩ

IV. RESULTS

In order to visualize the discharge response of battery, step response is applied to battery or discharge model is implemented in MATLAB as shown in Fig. 9. From the model implemented on hardware it has been observed that, battery voltage rapidly decreases ass the SoC level reaches to 40%. That's why SoC of the battery can be maintained to increase the life span of the battery. To apply the balancing algorithm, all the cells are initialized with different SoC 89%, 86%, 80% and 74% respectively so that 15% SoC difference, 1.2 Ah exists between highest and lowest SoC cell. Moreover, SPDT (single pole double throw) switches are used with 33mF capacitance and effective series resistance 25 $m\Omega$. Results of active and passive balancing are shown in Fig. 10 and Fig. 11. From Fig. 10, it takes 2.5 hours (9000 seconds) to balance the SoC to the lowest SoC level of cell by dissipating the external energy through resistor and 6000 seconds in case of DTSC. However, resistor shuttling method cannot be used individually due to high energy dissipation and rise in temperature of the battery pack and extra cooling arrangements are required to maintain the temperature of the battery pack. Energy dissipation for passive balancing is much high i.e. 436 mWh as compared to the DTSC where it is only 105 mWh.

When these two topologies are combined ,commonly called HCBA, are implemented on hardware, results are quiet good as compared to individually one as shown in Fig. 12. It takes 2 hours to balance the all battery pack. Although the balancing time is little bit higher as compared to DTSC, but compromising little on balancing time allows to utilize the 100% battery capacity which is not possible in DTSC as 4% SoC difference exists after balancing. In Fig. 13, terminal voltages of along with the current transfer among batteries are shown. The current drain away from the battery is taken as positive and current taken in to the battery is referred as positive. The cell 1 and cell 2 experience discharging process and current is taken away from these cells. Similarly, cell 3 and cell 4 experience charging process as current is being transferred from cell 1 and cell 2 and referred as negative current. The total energy losses in Wh (watt-hour) during the charge balancing can be computed by subtracting the cell's energizes summation before the balancing and after balancing. As SoC difference reduces, the energy dissipation also reduces. In

Fig. 14, little increase in energy dissipation when passive balancing takeover the control, however, this increase in energy dissipation can be neglected.

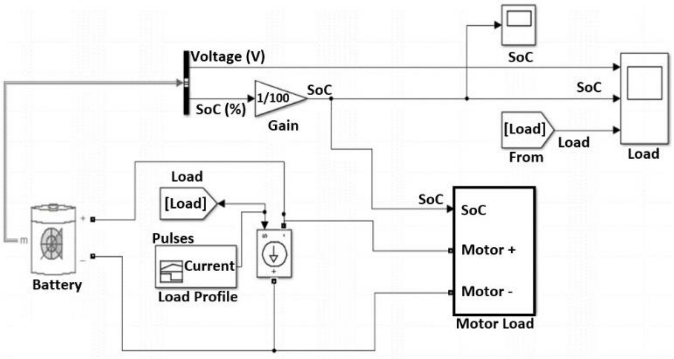

Figure 9: Simulink Model of Battery Discharge

In addition to this, after balancing the battery using the proposed balancing algorithm, it is exposed to load as shown in Figure 8 and compared the results with the algorithm discussed in [14].

When the proposed algorithm is applied on real time, it has been observed that 16% increase in discharge time observed which shows that if hybrid charge balancing algorithm is used to balance the charge in the battery, the drive range can be increased up to this level (16%). Hybrid charge balancing algorithm can be applied all range of SoC difference and gives the maximum utilization of capacity of the battery pack. Moreover, no complex control is required to transfer the charge between the cells which makes it best candidate for PHEVs. The simulation is run by varying different frequencies ranging from few hundred hertz to 10 kHz but the best results are obtained as shown in Fig. 12 at 400 Hz. But increasing the frequency higher than 10k will not produce any effect in balancing the charge. However, battery model used for simulation also depends upon the characteristics of the battery. The battery model which is used to simulate the results was “Extended Partnership for a New Generation of Vehicles (EPNGV)” as discussed in [7]. This battery model includes many features like SoC, cycle number prediction, different variable, parameters in the function of SoC, temperature of the battery pack as well as State of Health (SoH) of the battery pack. The balancing time in HCBA can also decreased if fast switching devices like MOSFETS with less on resistance, less diode forward resistance and diode forward voltage. One of the main reason by replacing the relay with the fast switching devices is switching losses. Moreover, employing the relays to the circuit not only increase the system size but also creates the system complexity. However, switch implementation and its characterization is not the scope of this paper. In Fig. 14, power loss across for all capacitors having equivalent series resistance was summed over the time of balancing to get total energy losses. The general trend between number of tier capacitors and energy dissipation is that increasing the number of tiered capacitors decrease the energy loss because charge will face less number of capacitor or find less impedance path.

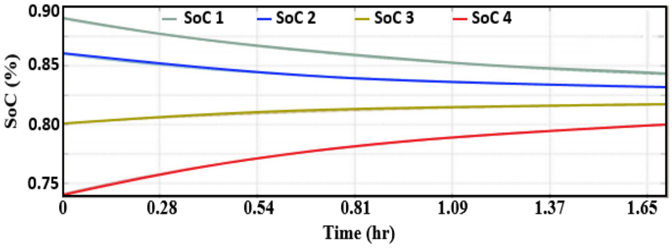

Figure 10: Result of Active Balancing for Four Lithium-ion Cells in pack (DTS

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