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Reconfigurable Battery Management System for Microgrid Application

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Abstract

Battery packs are formed by the interconnection of a greater number of battery cells. These battery packs are used in many electrical and electronics applications like sustainable energy systems, robotics, electric/hybrid vehicles and energy storage system in microgrid and smart grids. As a result, battery-based applications require a well-designed battery pack. Most of the research articles deal with the protection circuit, cell-balancing approach and battery management system. Nowadays, researchers are looking into reconfigurable based battery pack design to overcome the issues faced by the traditional system and conjunction with battery management systems like safety problems, low reliability, less energy efficiency and short lifetime. The most important characteristics of a reconfigurable battery management system are the arrangement of battery dynamically reconfigured concurrently depending upon the current status of battery cells using switching control according to load demand. Numerous research articles pertaining to reconfigurable battery pack techniques have been designed and implemented in real-time that makes the cell balancing condition at the time of charging/discharging cycle and also offer the fault-tolerant capability. This proposed chapter gives an overview of the reconfigurable battery system along with its challenges.

Keywords: Reconfigurable, battery management system, cell imbalance, state of health, state of charge, rate discharge effect, rate recovery effect, sensors

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6.1 Introduction

In recent years, the requirement of power generation is improving to greater extent to meet the required demand. The effect of environmental factors and rise in economy relating non-renewable energy sources-based power generation enables to look into sustainable energy sources-based power generation. Solar PV, fuel cells and wind are the renewable energy sources which have been deemed clean, inexhaustible, unlimited, and environmentally friendly. This forces the power industries to generate power through renewable energy sources and to realize their required demand partially. The government policies are also insisting on the same. The renewable energy sources like photovoltaic (PV), wind energy, hydro and fuel cells are not available to harness the energy for the entire day which directs towards the implementation of the energy storage system [1].

Currently, researchers are focusing mainly on the smart ways to use the batteries. The variety of optimization algorithms, scheduling method, and control techniques have been extensively studied to enhance the performance of the batteries so that it accomplishes complete operation automatically and improves the lifespan of the battery. Batteries are available in different sizes. Based on the applications, a few numbers of batteries are assembled together as a battery pack to meet the required load demand. Every battery exhibits numerous non-linear characteristics, it enables performance degradation. The performance improvement of the battery pack is the major confronting issue for the researchers. In order to fulfill the safety and reliability issues, battery packs are usually employed by the management system which takes care of monitoring the charging/discharging status and health status of the battery packs [2].

Static Battery management system (S-BMS) or traditional BMS are constructed using more of cells/batteries connected in fixed arrangement configuration such as series, parallel or a combination of these two to satisfy the requirement of load current and voltage. This method of battery management employed in harsh environments leads to reflect its individual cell characteristics because of uneven temperature gradient profile across the battery pack, non-uniform aging patterns or differences in their manufacturing tolerances [3]. Therefore, unbalancing in battery/cell occurs which in turn reduces the usage of entire battery pack. Thought of going for second time usage of battery packs, it creates furthermore complexity because of small difference in characteristics of every individual batteries would have been manifold at the first life of final stage. The optimization of S-BMS has been carried out using different scheduling techniques. The scheduling technique reported in Ref. [4] considers the charging-discharging time periods for scheduling whereas utilizing the battery behaviors like rate capacity effect and recovery effects are considered in Ref. [5]. These scheduling algorithms are preferred mostly for small scale battery management systems such as mobile devices as well as laptops. This method is not suitable for large scale battery management system. A promising solution is so called a reconfigurable battery management system (R-BMS), which overcomes the issues faced in traditional BMS and also applicable for large scale applications. Dynamic load conditions required applications like EVs are predominately works with this R-BMS in better way. The unique features of R-BMS are full utilization of battery pack, high fault tolerance and provide extended lifetime.

In this chapter, modeling of battery cell along with its characteristics and overview of the existing R-BMS topologies have been discussed. An overview of real-time implementation in design aspects and thermal management system of the battery is also addressed. Furthermore, various challenges to be faced in every sub-block which are to be anticipated at the time of real-time implementation, thus giving the directions towards the future research scopes.

6.2 Individual Cell Properties

In this section, the battery properties like the modeling of the cell, State of Health (SoH), State of Charge (SoC), battery life, rate discharge effect and recovery effects are discussed.

6.2.1 Modeling of Cell

Developing the accurate battery modelling gives the exact characteristics under various situations. In this section, summary of few commonly adopted methods are discussed.

6.2.1.1 Second Order Model

Generally prepared second order electrical modelling with the two set of coupled resistor and capacitor (RC) pair with a single resistor in series is reported in Ref. [6] and as shown in Figure 6.1. In this method, one RC pair is dedicated to short term instantaneous response and the other one is used for long-term as well as the slow response of voltage (v) and current (i) of batteries. But most of the cases, only one RC pair (i.e., single time constant) is commonly employed to simulate the long-term slow response characteristics of the batteries.

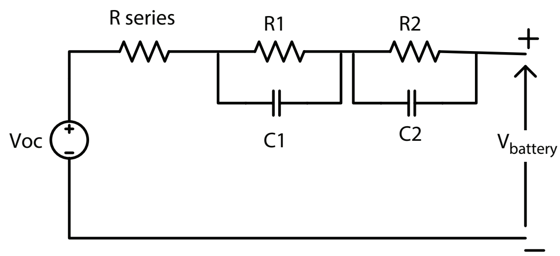

Figure 6.1 Battery equivalent electric circuit.

Where, R_{series} denotes the internal or series resistance, R_1C_1 pair is responsible for short term response, R_2C_2 pair is dedicated long term response for characterizing the real time batteries and V_{oc} denotes the battery open circuit voltage.

Consider the state variables are voltage drop across R_1C_1 pair (V_1), the voltage drop across R_2C_2 pair (V_2) and SoC. Therefore, the dynamic behavior of the battery using state-space model is given in Eq. (6.1).

$$\begin{bmatrix} \dot{v}_1 \\ \dot{v}_2 \\ \dot{SoC} \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_1C_1} & 0 & 0 \\ 0 & -\frac{1}{R_2C_2} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ SoC \end{bmatrix} + \begin{bmatrix} \frac{1}{C_1} \\ \frac{1}{C_2} \\ -\frac{1}{3,600C} \end{bmatrix} \bullet i + E.v_n \tag{6.1}$$

Where, C represents battery rated storage capacity in ampere-hours. v_n & E denote the noise and system matrix.

6.2.2 Simplified Non-Linear Model

First order battery modelling with non-linear characteristics is discussed in Ref. [7]. This modeling is widely used and adopted in MATLAB/Simulink.

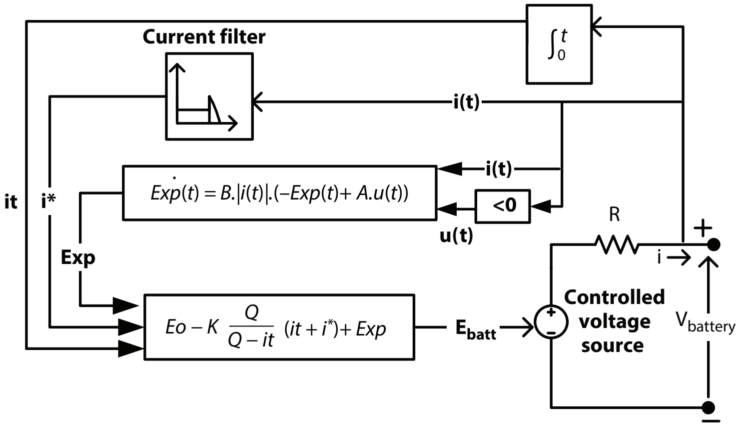

Figure 6.2 Implantation of battery model in MATLAB/Simulink.

The work presented in Ref. [8] deals about models of different variety of batteries, Li-Ion based battery modeling is discussed here. The charging as well as discharging analytical equation of Li-Ion battery is represented by Eqs. (6.2) and (6.3) respectively.

$$V_{battery} = V_{OC} - R.i - K\frac{C}{it - 0.1.C}.i^* - K\frac{C}{C - it}.it + A.\exp(-B.it) \tag{6.2}$$

$$V_{battery} = V_{OC} - R.i - K\frac{C}{C - it}.(it + i^*) + A.\exp(-B.it) \tag{6.3}$$

where, *Voc*, *R*, *i*, *i**, *C*, *K* and it are the open circuit voltage, internal resistance, current, filtered current, total capacity, resistance or polarization constant and used capacity respectively. *A* as well as *B* represents the amplitude of the exponential zone and inverse time constant. The discharge equation pertaining to Li-Ion battery implemented using MATLAB-Simulink model is depicted in Figure 6.2.

6.3 State of Charge

Measuring the quantity of charge in a battery with respect to its rated storage capacity is termed as State of Charge (SoC). It does not have a unit and commonly measured by the digital representation of 1/0—fully charged/discharged. The battery SoC at time t with storage capacity is denoted by Eq. (6.4) as follows

$$SoC = SoC_i - \frac{1}{3{,}600C}\int_0^t i(\tau)\,d\tau \tag{6.4}$$

where, SoC_i represent the storage the capacity of the battery at initial stage and i denotes the current. The current value is taken as positive while the battery is charging whereas negative when it is discharging.

Estimation of SoC is being difficult because of the listed issues such as unknown SoC at initial condition, sensor noise and fading of battery total capacity. The degradation of battery capacity over entire charge–discharge cycles and also self-discharge is the main factors restrict the estimation of SoC inaccurate value.

6.4 State of Health

Measuring the quantity of battery charging with respect to the exactly designed battery storage capacity is called as State of Health (SoH). In general, poor batteries are recognized using SoH only. This is also not having unit and commonly represented in the range of 0 (Not possible to store charge anymore), 1 (Ability to store charge upto specific rate capacity) or 0–100%. For instance, SoH represented by 0.8 means that 0.8 ampere-hours for a rated battery capacity of 1 ampere-hour. The battery capacity is reduced due to charging-discharging cycles as well as ageing. Therefore, it is necessary to track the value of SoH of a battery because it informs exactly regarding the actual battery capacity.

The various impedance (Z) based SoH measurement is reported in Ref. [9]. Alternative methods to estimate SoH are self-discharge rate, internal impedance/resistance method, the capability of accepting a charge, charge–discharge cycles, etc. Due to the problem conditions, the methods used for estimating SoH can also utilized to find SoC also. But these methods are specifically used for nickel–cadmium and lead-acid batteries. The Coulomb based counting the cycle is used for SoH measurement is discussed in Ref. [10].

6.5 Battery Life

Degrading of battery capacity is a generally happening event which reduces SoH or decreases the battery storage capacity. The factors pertaining to reduce the degradation of battery are metal deposition at the time of overcharging, electrolytes decomposition process and deposition of a film on electrodes [11]. These factors are considered for modeling in general anyhow it mainly depends on the type of chemistry occurs in the battery. SoH is used to quantify the left behind the capacity of the battery. Even though, measuring the endurance of battery is also important. Counting the cycle is generally used method to specify the capacity degrading process at the time of battery life cycle. An entire procedure for charging as well as discharging of the battery is termed as a cycle. In general, an endurance of the battery is to quantify the rest of the capacity after a specific cycle count.

The capacity degradation primarily depends on film deposition on the electrode caused due to oxidation of the cell according to the study reported in Ref. [12]. The film growth process is represented in Eq. (6.5).

$$\frac{\partial \delta}{\partial t} = \frac{i_k M}{L \alpha \rho F} \tag{6.5}$$

Where, i_k denotes the rate of current flow reaction and δ is the film thickness [12], M, α, ρ, L denote the constant of any particular battery. The fast charging (load current is higher) tends to fast degradation of battery capacity which directs to decrease the counting of a cycle. Hence, algorithms should be designed in such a way that maximizes the endurance of battery life with respect to cycle count by means of high capacity (SoH) as possible.

6.6 Rate Discharge Effect

A common factor that happens in all variety of battery is the rate of discharge effect, which proved by Peukert's law. If the discharge (current) effect is increased this makes the reduction of output energy in the battery. Due to the restriction of the inner electrochemical process in the battery, this causes the rate of discharge effect

$$C_p = I^k t \tag{6.6}$$

Where, *Cp*—the rate of storage capacity (A-h), *I*—current (A), and *t*—operating time (h). Assume that this effect is nil, then the operating time will be t = Cp / I, which is denoted as k = 1 in Eq. (6.6). In particle, all batteries operating time is t < Cp / I because of k > 1. The above property clearly shows that by reducing the current of individual batteries which increases its operating period.

6.7 Recovery Effect

The recovery effect is the most common thing that occurs in all the batteries. After discharge, the battery will become ideal which makes the voltage recovery done by the electrochemical reactions. If the discharge rate increases, this leads to the voltage drop in the battery. The above issue has overcome, by giving some rest to the battery which also extends its lifetime. The mathematical representation of the recovery effect is given below Eq. (6.7).

$$F_R : C_d \times t_d \times t_r \rightarrow V_{OUT} \tag{6.7}$$

Where F_R—recovery effect, C_d—discharge rate, t_d—discharge time, t_r—rest time and V_{OUT}—output voltage.

6.8 Conventional Methods and its Issues

A single cell or battery is not sufficient to meet the load demand so that a grouping of cells or battery requires solving the problem. Variety of grouping of batteries is done depending upon the specific load requirements such as higher current, higher voltage or higher power. The three types of topologies are followed in traditional battery management system as follows:

- Series connected
- Parallel connected
- Series-Parallel connected
    - Serially connected configuration
    - Parallelly connected configuration

Figure 6.3 depicts the four varieties of topologies realized in the traditional system. Every cell connected in specific configuration undergoes degradation in different level irrespective of the connection pattern.

6.8.1 Series Connected

Figure 6.3 (a) shows a series connection-based topology for the battery pack. According to Kirchhoff's voltage law, the total voltage is obtained through sum of the individual cell voltage in the battery storage system. In this arrangement, an enormous quantity of current is drawn for charging/ discharging which in turn to diminish the life span of the battery and may

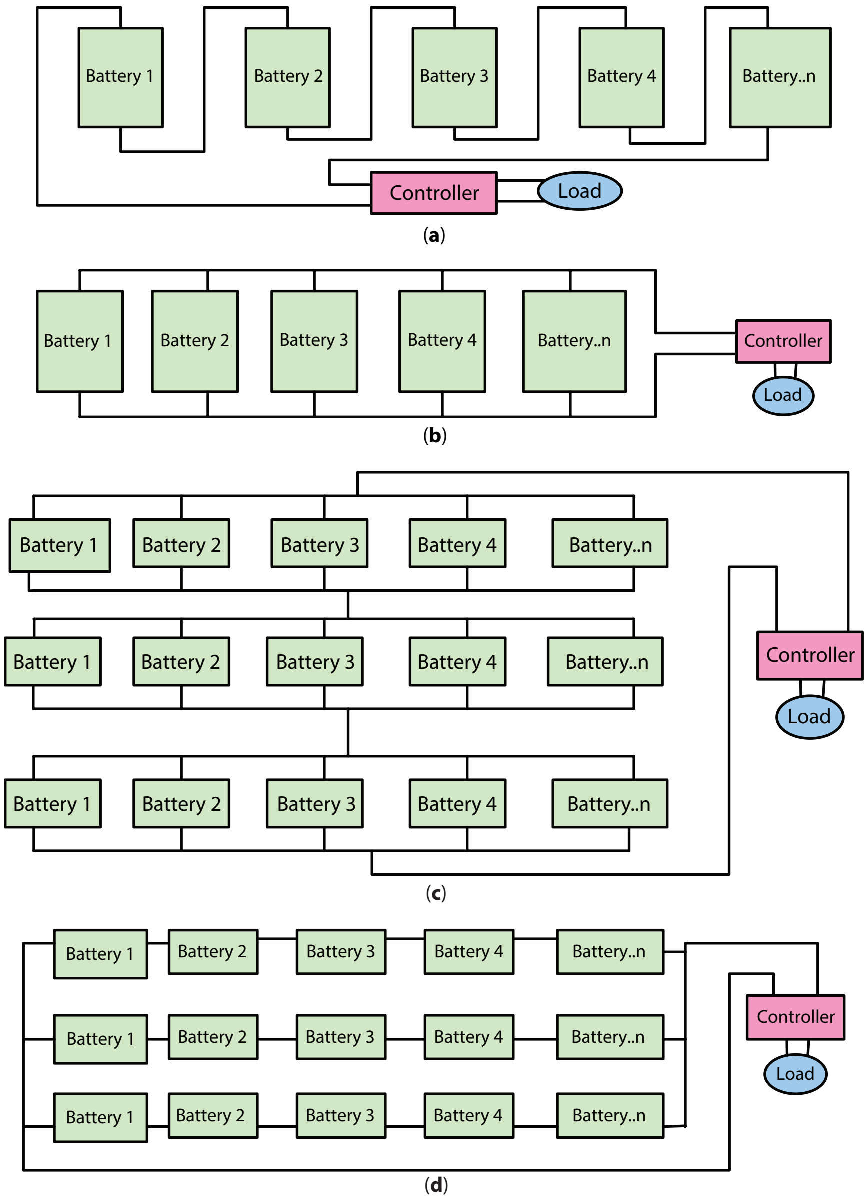

Figure 6.3 Existing topologies: (a) Series connection, (b) parallel connection, (c) PCC, (d) SCC.

start damaging the physical structure. Cell equivalence is to be considered to overcome these issues pertaining to series connection.

As a cell with less SoH or a faulty cell is available in a series connection leads to discharge very fast than the other group, without considering the load requirement. Therefore, maximum working time is reduced. Due to the series connection of cells, a variety of internal resistance of any cell in a group tends to not much difference because of total resistance is the sum of the individual resistances. But in this series connection topology, variation in SoC/voltage in every cell is possible. This voltage imbalance amongst the cells leads to over-discharge and may also tend to damage permanently [13]. The active and passive method of balancing is available for series connection is reported in Ref. [14]. The external fault occurs in series connections are open circuit or short circuit. The open circuit fault in series connection topology makes the series connection ineffective whereas a short circuit fault leads to a rise in current drawing capacity and rapid change in temperature, finally directs to malfunction of the battery management system.

6.8.2 Parallel Connected

Figure 6.3 (b) illustrates the parallel connection-based battery pack topology. This method is more suitable for the energy storage system which draws more current. Due to the parallel connection arrangement, the existence of one faulty cell in a group creates unsafe to rest of the cells. The healthy cells in a group should balance the faulty cell lower output current relentlessly and thus reducing the life span.

Due to the parallel connection, charging/discharging of every cell is differ in tiny changes because of its internal resistance. While the operation of parallel connected battery connection, this directs a huge variation in current drawing capacity for every cell. Due to the parallel connection, the voltage across each cell is the same. This brings to self-balanced architecture forever and makes the same State of Charge (SoC) for each individual cell [15]. In contrast to series connection arrangement of cells, open circuit fault does not affect the regular operation however creates a burden to the rest of the cells in a group whereas short circuit fault makes very bad situation due to single fault tends to whole system damage or thermal runaway because of creating cascade connection of cells.

6.9 Series-Parallel Connections

A grouping of series and parallel connected cells are needed in order to improve the operating voltage and battery capacity. Series-parallel based topology comes into the category when both voltage and currents are to be improved.

The two different configurations of this topology are illustrated in Figure 6.3 (c) Parallel connected configuration (PCC) and Figure 6.3 (d) Series connected configuration (SCC). Inside a battery pack, the parallel string of cells is connected in a series manner to construct a parallel connected configuration. Due to parallel interconnection of each cell, self-balance by itself, there are fewer requirements for an external cell-balancing circuit. But the cell-balancing for module level is definitely needed. This unique characteristic is the most viable solution for higher capacity and higher current applications. The shortcomings of parallel-connected configuration are fault due to open circuit and leakage current. The short circuit fault occurs when the leakage current goes beyond the certain level which also directs into a similar type of faults in the rest of the parallel connected cells. The failure caused by the open-circuit is that it limits the power transferred from the energy storage system to load [16].

The series connection makes to improve voltage rating whereas parallel connection leads to enhance the current rating in SCC. This type of SCC is absolutely needed to satisfy the high voltage requirement and it also not possible for constructing a single battery to fulfil the high voltage applications like gird storage systems and electric vehicles etc. The extraordinary attention is to be taken when comes to the assembling of parts, maintenance and servicing of such SCC due to its higher operating voltage. In order to, increase the capacity of SCC by means of including 'n' number of series connected batteries in parallel to keep the operating voltage constant. The battery pack module level cell-balancing happens at the time of rest period because of their interconnection in parallel. However, the cells inside the battery pack are not balanced. This leads to the implementation of very complicated intra SCC based cell balancing circuit [16]. The defect may occur in the series-connected configuration are open or short circuit. The open-circuit directs to enhance more stress on the rest of the cells connected in a string. In the other hand, short circuit leads to total failure owing to thermal runaway. SCC is more prone to open circuit fault whereas less prone to short circuit fault.

6.10 Evolution of Battery Management System

Reducing the health degradation and improving the operating time of battery are the most challenging issue. Variety of algorithms is developed for discharging has been carried out previously. In order to improve the operating time, capacity rate and recovery effects are used in most of the methods. This section discusses about the optimization methods implemented for BMS, R-BMS and comparison also made for the methods to be discussed.

6.10.1 Necessity for Reconfigurable BMS

Nowadays, Static-Battery Management System (S-BMS) is broadly employed in large scale application like electric vehicles, energy storage in smart grids, independent power grids for homes and robotics. The optimal utilization of battery packages is required for higher operating time as well as increasing battery life. Increasing the operating time of battery cells by utilizing fully is done through scheduling algorithm. Scheduling algorithm requires more than an actual number of battery cells because it depends on the backup battery cells to meet up the demand when one of the battery cells is switched off. Adding extra battery cells in small scale application is possible solution whereas it is impossible to implement for large scale applications due to the complexity of the circuit and cost. In addition, the scheduling algorithm is easily implemented in a single battery package whereas module level scheduling creates more computation complexity owing to different parameters like SoH, SoC of every module and load demand [17]. In scheduling algorithm, problems occurring due to non-linear characteristics of the battery are not exactly focused. Hence optimum solution cannot be possible in this scenario.

Voltage regulators are used in S-BMS to keep the voltage level constant when discharging as well as it offers multiple voltage output. For providing multiple voltage output, DC–DC converters are employed and efficiency of the converters depends on output and input voltage level in the form of voltage regulators. If the input voltage to the regulators is less than the operating voltage leads to more power loss, in turn, reduce the efficiency. Therefore, dealing with this issue by means of a voltage regulator is not a feasible solution. The fault tolerant is the primarily significant need for a large-scale battery management system. Currently, the scheduling algorithm selects the particular cells in BMS is carried out when it is in working condition but there are no actions are taken against to remove the cell permanently once it is faulty or over discharging from the particular cell. This issue is overcome by incorporating the reconfigurability in BMS. In this section, various topologies available for R-BMS are discussed in detail. The re-configuration with BMS improves the following features like increase in operating time, fault tolerance and improvement in efficiency.

6.10.2 Conventional R-BMS Methods

On the other hand, a Reconfigurable Battery Management System (R-BMS) utilizes the batteries that are connected automatically in battery packs through switching logic control to meet the necessary demand and change in their inherent characteristics such as voltage, withstanding capacity and so on. This topology produces less power loss compared with power converters to satisfy the preferred load curve. There are various reconfigurable topologies are available in the literature [18]. The topologies are 1) First design, 2) Series topology, 3) Self X topology, 4) Dependable Efficient Scalable Architecture (DESA), 5) Genetic algorithm-based topology, 6) Graph-based topology and 7) Power tree-based topology.

6.10.2.1 First Design

Figure 6.2 shows the First design which is more preferred to fulfil the power requirement in minimum value through changing the voltage of each battery cell dynamically by considering the non-linearity characteristics of each individual battery. This reconfiguration method adopts any of the arrangement such as series, parallel and series-parallel topology by controlling the switches to meet the load demand. This design obeys the basic concept like the same voltage in the parallel circuit and same current in series circuit.

The hardware model is developed with reconfiguration done for each cell using 5-control switches as depicted in Figure 6.4 which works to create a variety of configuration. Every battery/cell in the battery packages is arranged in series or parallel to the nearby cell or desperate entirely from the pack is called Full reconfigurability. Consider the two modules connected in SCC topology reported in Ref. [19] taken as an example. In this topology, the total battery pack goes below a rated voltage, the SCC turn out to be in series connection to improve the voltage level. The switches are opened or closed in order to realize the proposed reconfiguration arrangement. The complete pack is utilized for a second time only when the rated voltage is reached another time. The operating time and capacity are improved by 14.58 and 28.5% respectively adopting this reconfiguration topology.

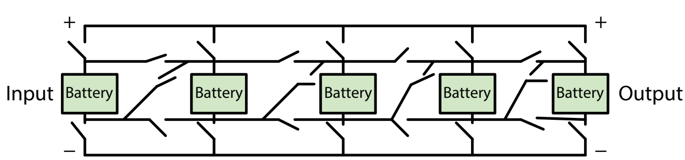

Figure 6.4 First design having 5 switches per cell.

6.10.2.2 Series Topology

Series topology-based reconfiguration in Figure 6.5 exploits the battery usage completely. This results in more operating time, improvement in reliability and enhanced tolerant capability to failures of single/multiple battery cells. Each cell with two controllable switches which makes a series connection or bypass the connection as shown in Figure 6.3. The battery cells in a pack automatically reconfigured in a series manner when the threshold voltage is reached nearby to keep the voltage at the required level. In the same way, the cells are connected in bypass in charging mode while it initiates to overcharge to avoid the requirement of cell balancing.

The safety pertaining to the battery pack in real-time is ensured through the sensors' data in this topology. This topology reported in Ref. [20] produce the maximum energy capacity of 66.7% even at the time of worst battery failure situations and gives the maximum efficiency of 98% under maximum load by taking power dissipations of switches into consideration.

6.10.2.3 Self X Topology

Figure 6.6 gives an idea about Self X based reconfigurable method. Here, X means that Reconfiguration, balance, healing and optimization of battery cells. The 'N' cells are connected in parallel as a single string which

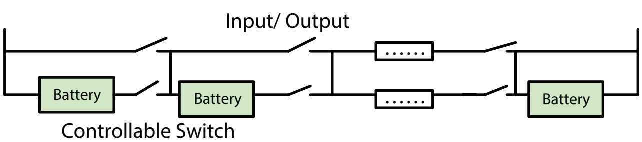

Figure 6.5 A series-connected reconfigurable battery pack.

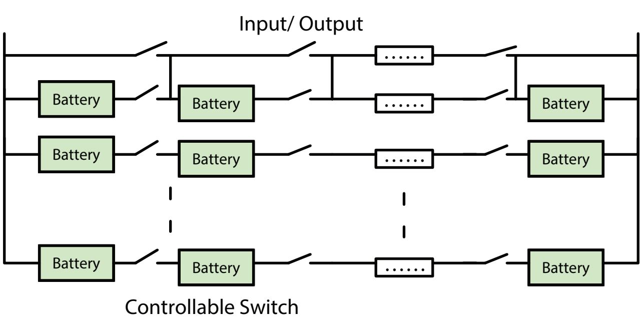

Figure 6.6 A Self-X reconfigurable multi-cell battery pack.

is isolated or connected by means of individual switches. The number of strings 'M' is connected in a series manner which is bypassed through a single switch per string. Therefore, totally M × (N + 1) switches are needed to implement this arrangement as depicted in Figure 6.6. The hybrid battery model reported in Ref. [21] is used for real-time application because of less computation time, higher accuracy in prediction of SoC. This method comprises of three sections namely cell pack, switching circuit as well as the BMS. The model based SoC estimation is carried out in BMS through current, cell voltage and temperature. This reconfiguration method along with an optimal scheduling technique allows finding out the exact faulty battery cells from the connected topology and also makes the fault-tolerant based management system with less number of switches.

The limitation of this topology is that it does not permit two cells of the similar string in series or two cells of dissimilar strings to be connected in parallel. The strings are chosen according to the current demand and SoC. The optimum value of current and voltage obtained from the control module by means of the following trade-offs,

1. The output voltage should be chosen in order to work the DC-DC converter at retaining maximum efficiency as well as higher voltage gain.
2. Each the cell should be utilized only when its rated capacity meets the load demand.

Dynamic reconfiguration is used to separate the faulty cells by healing those cells. The dynamic reconfiguration with this topology using an optimum scheduling algorithm [21] produces a fault tolerant system with minimum quantity of switches.

6.10.2.4 Dependable Efficient Scalable Architecture Method

DESA reconfiguration (Figure 6.7) of the battery management system is implemented where the integration and controlling of large-capacity battery packs application with less number of switches using Controller Area Network (CAN) bus for making communication between local and global battery management system. The global and local BMS based on monarchy relationship [22] in which the instructions from global BMS are accomplished through local BMS. The necessity for a local controller is the smallest amount in a fully centralized systems because the global controller works on higher speed in switching configurations as well as in fault detections using monitoring the individual cells performance directly

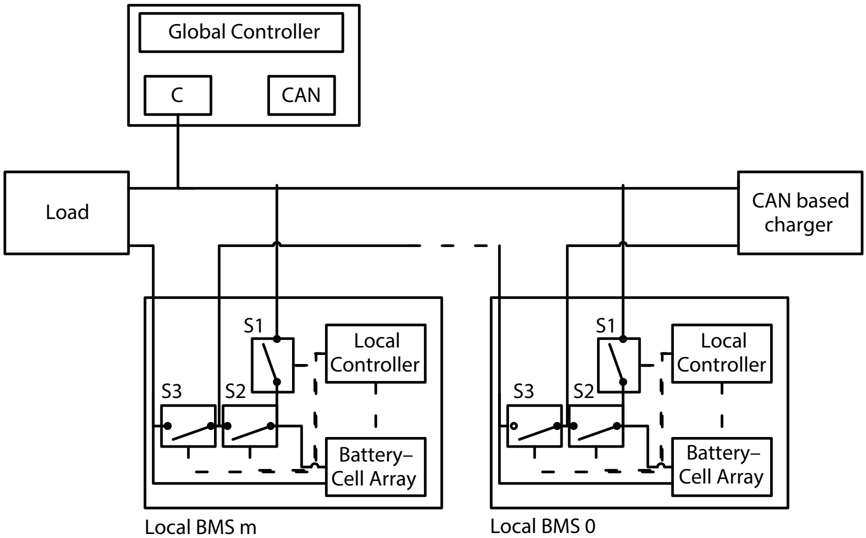

Figure 6.7 Schematic diagram of DESA.

and controlling the switches according to the load demand. In the case of large battery pack applications, the computational complexity due to the global controller is enormously high and therefore DESA based centralized topology works better in that situation.

The major disadvantage of this method is that the total battery management system will get failure if a fault takes place in either local or global battery management side. A logical switch configuration based algorithm discussed along with DESA architecture is employed through a global controller to direct a local controller using three array level switching namely parallel switch (S1—P-Switch), series switch (S2—S-Switch) and bypass switch (S3—B-Switch) as illustrated in Figure 6.7. This DESA topology works on the principle that neither CAN bus nor global controller fails [22]. The entire system gets failure when the fault occurs in any of these two components of DESA because of communication issues.

DESA with derived cost model has the capability to generate cost effective battery pack. This topology proved that improving reliability, saving cost and reducing the service cost in the order of 2×, 7× and 4.2× times respectively compared to traditional battery models.

6.10.2.5 Genetic Algorithm-Based Method

The well-established dynamic reconfigurable method using genetic algorithm-based topology is depicted in Figure 6.8. This reconfiguration

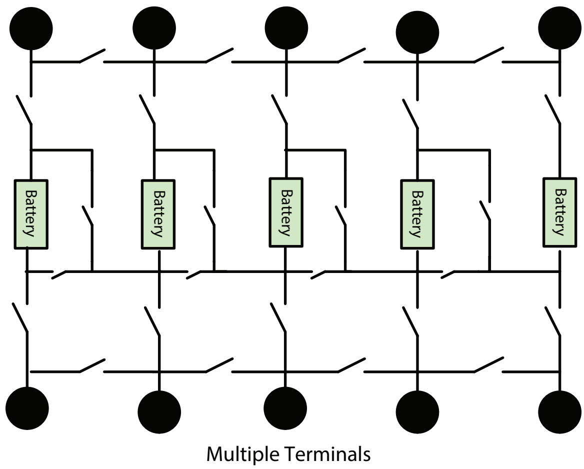

Figure 6.8 Genetic algorithm based topology.

technique has two important goals which are to reconfigure the battery management is in an online to get the information regarding faulty batteries and provide the numerous output voltage terminals. The syntactic and semantic bypassing mechanism based genetic algorithms are used to generate configuration. In case of syntactic bypassing mechanism, the switching or bypassing of the cell from series to parallel as well as vice versa when no fault happens and the faulty cell is isolated [23]. In the other hands, the semantic bypassing mechanism directs meaningful to the syntactic mechanism by means of taking decisions that which group of cells in a string should be utilized at the time of operation in such a way that every cell maintain the constant voltage at the terminals and degrades all the cells at the similar rate.

Furthermore, this genetic algorithm along with scheduling provides optimum utilization of every cell in a battery pack. This work is established with six switches which enhance the fault tolerance the capability of BMS and to prevent the use of DC–DC converter for providing dissimilar voltage terminals.

6.10.2.6 Graph-Based Technique

A graph-based algorithm to reconfigure the battery management system shown in Figure 6.9 is the most suitable technique for satisfying the load requirements in real-time. In a traditional system, ineffective voltage regulators are used whereas multi-terminal output terminals are provided in

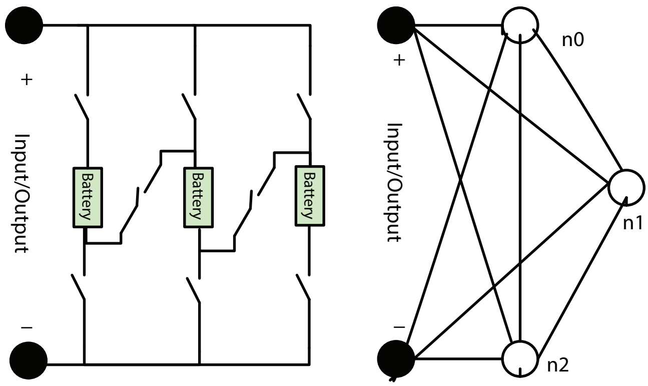

Figure 6.9 Graph based topology and paths as graph representation.

case of reconfiguration battery management system. Two switches per battery pack and three switches per battery cell are used in graph-based technique is as shown in Figure 6.9.

Higher efficiency obtained using the effective scheduling of charging/discharging and resting time in a proper way [24]. The performance degradation of battery packs occurs due to unbalanced cell in a battery pack and SOH of the rest of the cells. In most of the literature, the SoH factor is not addressed effectively expect the study carried out in Ref. [25]. The paper proposed in Ref. [25] deals about two algorithms such as Full-SHARE algorithm (SoH Aware RE-configuration algorithm) as well as Partial-SHARE algorithm with graph based approach is used to achieve for fully and partially reconfigurable battery packs. The simulation and experimental evaluation report that Full- and Partial-SHARE algorithm produces 10–30% more capacity compared to the SOH-oblivious system. The proposed algorithm performs well even with harsh cell imbalance conditions and increases the battery pack capacity in the range of 10–60% [26].

6.10.2.7 Power Tree-Based Technique

The power tree model based reconfiguration system is visualized in the form of an inverted tree in which the overall battery pack considered as root and individual sub-block pack considered as leaves. The overall capacity of battery packs are divided into sub-packs consists of series (Ns) and parallel (Np) combinations which are defined as the division of (Ns × Np) packs into a set of 'n' sub-packs (Nsi × Npi), where, i = 1,2,3,…n. The atomic node is defined as the division is carried out till the value which is

Table 6.1 Comparison of various reconfigurable topologies properties.

S. No.	Reconfiguration topology types	No. of switches used	Operating response	Computational difficulty	Hardware difficulty
1.	First Design	5	Low	High	High
2.	Series	2	Medium	Low	Low
3.	Self-X	2	Medium	Low	Medium
4.	DESA	Nil	High	Medium	Medium
5.	Genetic Algorithm	6	High	High	High
6.	Graph	3	High	High	Low
7.	Power Tree	3	High	High	High

indivisible. However, the number of divisions is limited by power range level. This division-based algorithm has features such as fast power reallocation (FPR) and fast failure recovery (FFR). The number of additional cells is reduced to produce an optimum number for a stipulated time period (T) using A* heuristics search [27] in power tree-based topology.

This re-configurability topology is not having a direct relationship with the number of switches used. Therefore, it is not the best method so far. The multi-chemistry-based energy storage systems are capable of producing high power and high energy to the load [28] by means of taking into consideration of various cell chemistry properties apart from the methods mentioned above. In the next method, distributed R-BMS reported in Ref. [29] claims that increased reliability, scalability, the possibility of adding/disconnecting the modules and failure identification controller to detect a single battery pack rather than the entire module. Due to distributive nature, maintenance and replacement is easy compared to traditional BMS. The performance of the power tree is better than with other reconfigurable topologies are illustrated in Table 6.1.

6.11 Modeling of Reconfigurable-BMS

The major goal of R-BMS is increasing the reliability of cell faults and efficiency of the battery packs. For constructing the R-BMS requires a greater number of passive circuit elements of switches. This leads to enlarging the complexity issues and affects the reliability and predictability of the system. The testing at that design phase enables the designer to think of real-time implementation in the easiest way. To implement this technique, R-BMS is to be considered as a Cyber Physical Systems (CPS). CPS is a method in which modelling of a variety of components as modules or blocks and tests the integration of the modules. The simulation of designed R-BMS with CPS creates the platform to identify the major issues like failure of cells and switches, responses to load variation, reconfiguration speed and other parameters at the time of design phase itself. In addition to it, extra features to be included in R-BMS can be done through updating the modular part alone.

The real-time embedded system which collects the data directly from the physical environment is referred to as time-dependent data. This data should be processed further to take a decision for generating the actuation signals. The actuation signal is very simple in case of small scale networked embedded systems. On the other hand, issues such as stochastic behavior and timing variability [30] occur in large scale application. In R-BMS, the time dependent data sensed in real-time is the foremost action to be done for constructing battery reconfiguration system. The differential equation is preferred due to the collected data in continuous time. The realization of reconfiguration in BMS is carried out by means of actuating the switches in predefined specific condition. For example, each cell comprises of two definite states in series connected topology in which one state is being used to make a series connection in the network and another is used to bypass from the network. This approach reveals that predefined unique set of patterns for each configuration of R-BMS topology and different switching states for the configuration used. From this statement, R-BMS is considered as Finite State Machine (FSM) and each state is regarded as a single configuration. Therefore, the reconfiguration-based modeling techniques work on the input of real-time sensors data as a function of the differential equation and actuate the switches in a discrete set of values in R-BMS for changing the state from one to another. Thus, the entire system is modelled in hybrid in nature which consists of both continuous and discrete characteristics.

6.12 Real Time Design Aspects

Reconfiguration in a BMS controls every cell module. Therefore, performance, robustness and fault tolerance of CPS should be evaluated. R-BMS is divided into three modules such as sensing module, decision control module and actuation module. Getting stable data is the biggest challenging task in the sensing module. For calculating the SOH and SOC of each battery pack or cell is the most difficult task due to its non-linear characteristics, which creates further complexity by adding the reconfigurability feature. The next module is the control module in which a variety of algorithms and techniques are tested for improving the decision-making capability in a smart way to handle any hard situation. The actuation module is the last module comprises of switches in which configuration of cell or battery modules are controlled. This stage is the difficult task where the control signals from the decision control module to be realized in a manner which neither the load nor the battery packs are affected to ensure the safe working condition. Some of the challenging factors faced to implement the R-BMS like thermal issues and circuit safety are discussed in the review paper [31]. This section deals about the various challenging factors to be considered while designing stage itself in R-BMS. There are sensing module stages, decision control stage and actuating signal generation stage.

6.12.1 Sensing Module Stage

In this module, sensors design and development for sensing the different parameters pertaining to battery management and its deployment are focused. In addition, an efficient way to recover the data from the sensor modules is also carried out in this section. Sensors data from sensors are playing a vital role to maintain the BMS to operate within the control limits and produce the optimized output. Design of sensing circuit with fault detection for each battery pack increases the circuit complexity and reliability. This directs to rapidly affect the computational tasks involved in turn results in a decrease in overall simplicity. Therefore, for better improvement trade-off the parameters are essential. If the number of sensing circuits for each battery is decreased in order to decrease the circuit complexity leads to poor battery fault detection and also choosing the specific battery to meet the required load demand. Hence, the benefit of adding the reconfiguration feature in a BMS will not be solved. For implementing a large scale BMS, researchers [32] adopted the best sensing technique in which sensors are chosen to acquire data by means of heuristics and acts accordingly. The same technique has to be utilized to realize the R-BMS also.

6.12.2 Control Module Stage

This is the heart of the R-BMS in which algorithm is employed to characterize the reliability, scalability and re-configurability features. The algorithm implemented in this control module should provide the assurance to utilize each cell fully in the particular battery package in effective manner and structured way. From the literature survey, the following are the design features used in control module.

6.12.2.1 Health Factor of Reconfiguration

First of all, to verify whether the reconfiguration with the proposed algorithm gives the optimum outcomes or not is the major goal for implementing the R-BMS. Depending upon the load demand, the cell configuration should be chosen to produce the best result. Consider the following example to clarify the above-mentioned factor. In order to meet the load of 50 V with (10 × 1) or (10 × 2) Lithium based cells of the mean voltage value of 5 V per cell. Here, 10 represents the number of cells in a pack and 1 & 2—denotes the current handling capacity of each pack respectively. According to the load current requirement, one of the battery packs is to be assigned. In case, load demands 1 A in the whole sum, the algorithm should choose a 10 × 1 battery pack whereas load requires more than 1 A in total (less than 2 A), 10 × 2 battery pack will be the desired choice by the algorithm due to the fact that cell degrades its health performance while more than its rated capacity being drawn. Therefore, defining the health factor is the basic requirement for each configuration of R-BMS according to load demand. Most of the existing algorithms in the literature fail to address this Health factor. Implementing the smart algorithms with health-factor will be the future scope of research in the area of R-BMS.

6.12.2.2 Reconfiguration Time Delay and Transient Load Supply

R-BMS employs to meet the load demand with no delay at any circumstances. In dynamic reconfiguration of battery packages, two challenging issues such as re-configuration time delay and transient load supply [33] are in front to distribute the power in an uninterrupted way. Re-configuration time in R-BMS is defined as the minimum time required for creating a new arrangement of cell configuration. The system performance degrades specifically for large scale dynamic reconfiguration of battery packs in which every sensor available in the system operates uninterrupted way. It requires the fastest response in reconfiguration at the time of load changes, over discharge and any battery fault conditions. The reusing the last used switch configuration leads to produce very less reconfiguration time [34]. Coordinated switching based on agile reconfiguration is the future scope of research to reduce the reconfiguration time.

The other factor influences the large scale dynamically reconfiguration system is to supply the load current at reconfiguration time. For example, consider the following case is that the load demand varies from 200 V (high voltage), 4 to 100 V, 8 A (high current) and reconfiguration time of 1 min. For meeting the load current of 8 A in a single minute is not an easy task. To overcome this issue, the secondary power supplies based on supercapacitor is the best option to meet up the transient load currents. This is also scope for extending the research in the field of the battery management system.

6.12.3 Actuation Module

The hardware pertaining to R-BMS such as processors, switches and cells comes under this section. Most of the operations carried out in this module only. If the actions are taken in the wrong manner, it leads to failure of the entire R-BMS. Some of the design features with respect to this module is explained as follows.

6.12.3.1 Order of Switching

The optimization technique discussed in Section 6.3 deals about the rules and algorithms to choose a few numbers of cells or battery packs depending upon its specifications. Even though, the order of switching is not discussed so far. Order of switching is essential in R-BMS because inappropriate manner of switching sequence may lead to an unfavorable fault like a short circuit. Consider the battery pack consists of four cells (C1, C2, C3 and C4) with four switches arranged for reconfiguration as depicted in Figures 6.10 to 6.12.

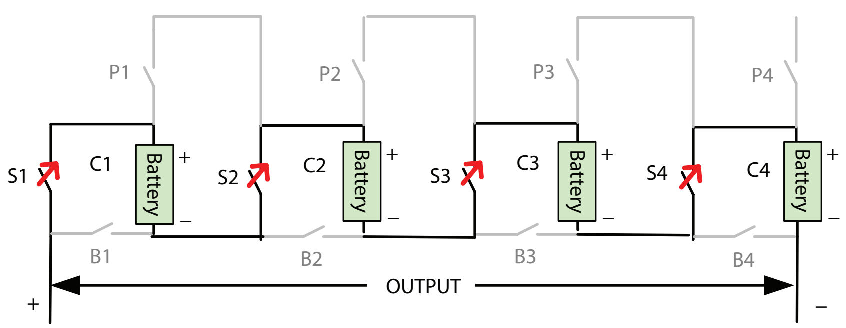

Figure 6.10 4S configuration-based order of switching.

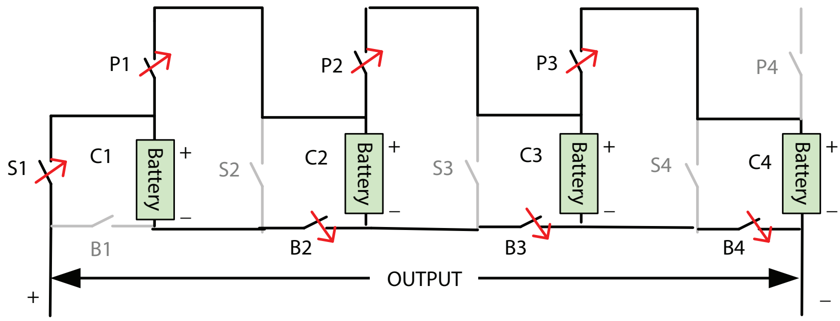

Figure 6.11 4S to 4P configuration-based faults occurring switches.

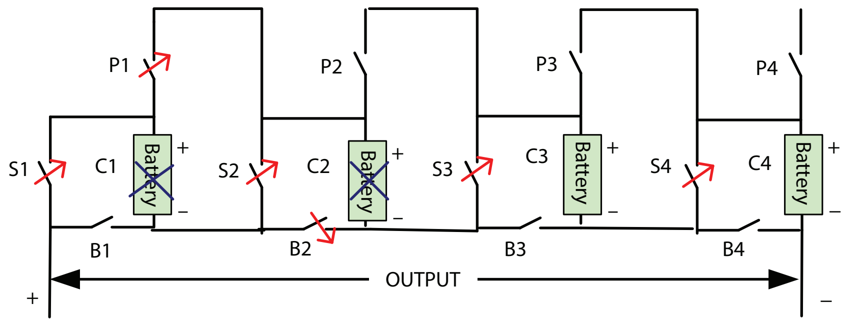

Figure 6.12 4P configuration-based order of switching.

The 4S configuration where all series switches are in ON state is depicted in Figure 6.10 and fault occurring switches where series switches are in OFF state is shown in Figure 6.11. The parallel configuration (4P) configuration of switches with ON state is illustrated in Figure 6.12. In order to have a reliable load condition, there must be transition from 4S configuration to 4P configuration. Thus, the S_2, S_3 and S_4 switches are changed to OFF state and then P_1, [P_2 B_2], [P_3 B_3] and B_4 are toggled to ON state. If S_2 and P_1 are in ON state, then cell C_1 is short circuited. Similarly, if S_2 and B_2 are in ON state, then C_2 is short circuited. In order to have smooth switching system, the need for derivative of switch dependency is must for dynamic reconfiguration. The chances of a short circuit are high when the system is connected in series configuration which can be seen in Figure 6.11. Thus, to avoid this conflict, the series switch should be in OFF state before parallel switch or bypass switch is switched ON. Thus, it can be stated that the serial switch is dependent on both parallel switch and bypass switch. Whereas, the bypass switch and parallel switch are not dependent on each other. Thus, an analysis of switching dependency is required to reduce the transition time and short circuit faults which in turn increases the reliability and efficiency of the battery reconfiguration system.

6.12.3.2 Stress and Faults of Switches

The performance of the reconfigurable battery pack highly depends on the switches which are highly sensitive in nature. The type of switch, position of switch plays an essential role in the performance of the battery system. Solid state switches are highly recommended over electromechanical relays for its reliability and safety. Because of electromechanical relays constitute of high voltages and arcs which affects the performance of the battery system. The only disadvantage of the solid-state switch is high power consumption. Generally employed solid state power electronic switches are MOSFET and IGBTs. Based on the requirement and applications, the types of switches are considered for the system. Generally, for high power application, IGBT switches are used whereas for high frequency application, MOSFETs are considered. The major drawback of the switches is its switching loss and voltage stress due to prolonged ON–OFF state. And moreover, to turn ON and OFF, the additional driver circuit is required which consumes the power. Thus, by using an optimal number of switches, the load on the system will be reduced and also the switching loss will also be reduced. Thus, to enhance the efficiency, enhanced—MOSFET with high depletion layer is generally used in the high power application.

The efficiency of the BMS highly depends on the switching loss. The power delivers by RBMS is high when compared to SBMS but the loss due to switches affects the system reliability. Thus, to increase the efficiency of the system such losses should be considered which is caused due to conduction and also by switching transient. The exact power loss as well as efficiency of the particular R-BMS topology is difficult to determine because of no standard on-off time for different switches employed over each cell. The switching in R-BMS is mainly depends on few factors such as the current flowing through the switches, the individual cell voltage, the voltage across it and the operating time of various modes which is highly unpredictable. Thus, a comparison of the previous topology is not possible unless the system has the same battery parameters and configuration of the standard test condition. In Ref. [21], the authors have configured Series topology and self X topology. The losses incurred due to switching are not enormous concern for the transition period between ON state to OFF state is approximately 30 min for implementing the application. But when as large battery packs are considered for the application, the switching loss may increase. Similarly, in Ref. [22], the authors implemented DESA disused about the switching losses caused by the system in the entire process of the conversion.

Thus, an in-depth analysis is required to build an R-BMS topology to enhance its efficiency. Providing a good trade-off between flexibility and efficiency, the number of switches is calculated in an optimized way. In order to increase the flexibility of the system, the number of switches is increased thus tends to enhance the switching losses. Since the reliability of Reconfigurable BMS are highly dependent on switching faults, analysis of faults such as "open" and "short" should be rapid to avoid any further serious faults. To identify single switch open circuit faults, short circuits, post short circuits and rest of the unknown faults happening in eclectic drive of EVs is carried out by a neural network technology, trained by a machine learning approach is reported in Ref. [35].

6.12.3.3 Determining Number of Cells in a Module

Reconfiguration of the battery management system does not overcome all the short comes of conventional BMS such as extended time and cell parameters. In order to estimate the available operational time, analysis of a number of healthy cells in the battery system is required [23]. Thus, to cope up with the problem of low operating time caused due to unhealthy cell, both scheduling and reconfigurable methods is must enhance the operating time as well as providing the backup cell. Thus, to maintain the longer functional period and operating time of the battery packs in R-BMS needs backup cells requirement compared to traditional systems. Additionally, exact quantity of backup cells needed by scheduling methods to that of the number of working cells in conventional BMS. Whereas, in RBMS the number of backup cells required is less than that of a number of the working cell, since they reconfigure themselves to provide extra time and also to reduce the cost and size of the overall system.

Thus, it is essential to analysis the optimized BMS which determines the number of cells required, operating time and cost of the system. The optimization can be done by analyzing the failure cell rate, load demand and failure or mismanagement of sensing devices. The optimization of the BMS system will increase the efficiency and reliability of the system without increasing the size and cost of the system.

6.13 Opportunities and Challenges

6.13.1 Modeling and Simulation

Graph model based reconfigurable battery system has few drawbacks. In this model, connectivity is one of the major issues in which out-degree connectivity to be found is not in a straightforward manner. The solution for this issue possibly lies in between conservative connectivity extremes along with spatial neighborhoods and all-to-all connectivity. Variety of connectivity architecture with exact constraints makes much understanding and also clarifies the advantages of more flexible systems. There is no integrated framework available for simulation of BMS till now. Therefore, developing software dedicated only for BMS is required with an increasing research interest in this area. Nowadays, researchers are developing simulation work by themselves using single battery modeling and constructing the design manually. This approach tends to rise in time requirement and short of a general framework for creating group effort in an easy manner.

6.13.2 Hardware Design

Hardware development is not explored very well. Two types of hardware design exist in practice. One which dedicated only for a single load with three switches per cell and the second one which is employed for more than one load with six switches per cell. The number of switches may be reduced from six by giving up a few loads. The number of loads is restricted in most of the practical applications. For considering the electric vehicle application, drive motor alone requires high voltage and rest of the secondary appliances operates on low voltage in the range of 12 V. The reconfigurability or modular based battery management system is preferred for large scale applications. One of the field study reports [36] proved that approximately 8% of the entire weight devoted to switches and associated elements. Depending upon the level of reconfigurability, this value can be increased.

6.13.3 Granularity

Granularity is also having an avenue in BMS. In case of small-scale applications, reconfiguration of each battery or cell is possible. However, it is not feasible in case of large-scale applications. Therefore, re-configuration is applicable only for modules (fixed number of batteries is connected in some configuration) not single batteries or cells. This makes the researchers think to solve the following problematic questions such as how much reconfiguration flexibility should be considered and what must be the size of the fixed configuration module? In addition, the query may take place to design a module whether it may be SCC, PCC or hybrid of both.

6.13.4 Hardware Overhead

Evaluation of hardware, overhead is an added issue coupled with granularity. The switches with least switching losses of 1% are available for implementing R-BMS, rather than switching losses supported practical aspects are also to be considered for analysis. In general, these switches are needed for the specific works and resources because of the major issues such as control circuit size, overall losses incurred by different battery configuration and cost. The performance of switches plays on a vital role in overall system reliability which is also an equally important issue. Although, R-BMS deals specifically about the cell or battery failure, it is not explored about if the switches get failure. The switch failure should be carefully analyzed for implementing in real time due to its quantity being used and importance on the reliability of the system. The extensive work to be done in this area particularly discusses the identifying the switch failure types, detection, forecasting of failure and impacts on the integration of R-BMS.

6.13.5 Intelligent Algorithms

There is possibility to enhance the small-scale stand-alone appliances such as tablets, smart watches and phones etc rather than large-scale applications. For extracting the battery tradeoffs in the best way to boost the operation time by creating high-level polices and having flexible batteries. These personal electronics gadgets are already equipped with extraordinary features like personal scheduling, motion tracking and so on. This information may be used to define the best policy automatically for each individual user. The user's information pertaining to their daily schedule and subsequent action makes the researchers build a smart intelligent algorithm to perform fast or slow charging depending upon the situation prevailing at the time. The future research gives the scope in the area of improving battery performance using high-level information.

6.13.6 Distributed Reconfigurable Battery Systems

The distributed re-configurable battery management system is an attractive research area as discussed in Ref. [37]. Currently, R-BMS works for centralized control which causes a bottleneck in the large-scale real-time control system. Due to the upcoming smart cells with communication and tracking performance to realize the distributed control network discussed in Ref. [38]. The design of smart cells available in present is performing the distributed control actions which are restricted to fixed connection topology. This directs to validate the capability of smart cells in R-BMs to maximize the overall performance is also a new research area to be explored.

6.14 Conclusion

This chapter gives an overview of the various optimization techniques existed so far to implement the reconfigurable battery management system in the best way. The discussion about the characteristics of the individual cell or battery is modeled using first or second-order approximation and measures the parameters such as SoC, SoH, battery life, rate discharge effect and rate recovery effect to check the healthiness of the battery are presented. An outline of traditional battery connection arrangement, cell imbalance, and faults pertaining to it are presented to choose the one for the required application. The evolution of dynamically reconfigurable battery management system from a conventional battery management system is also reported well to opt for it. The real-time design aspects along with challenges and opportunities also explained for creating interest to the budding researchers in the field of the reconfigurable battery management system.

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