SYSTEM AND METHOD TO BALANCE CHARGE FOR MULTI TANK SYSTEM VANADIUM REDOX FLOW BATTERY AND OPERATION TOGETHER WITH LITHIUM BATTERY IN HYBRID INTEGRATION

FIELD OF INVENTION

[0001] The invention relates to Vanadium Redox Flow Batteries (VFRB), Lithium Batteries (LiB) and more particularly for state of charge balancing in multi-tank systems.

BACKGROUND

[0002] The market for renewable energy has grown exponentially over the last few years, which necessitates low-cost energy storage solutions to make the levelized cost of storage competitive to convention electricity cost. Short life and fire safety concerns are slowing the adaptation of lithium batteries (LiB) for energy storage applications, despite their rapidly dropping cost below 300 USD/kwh and very high energy density.

[0003] While flow batteries offer a good solution for long-duration energy storage applications, their poor (energy) efficiency compared to LiB, large footprint, and high cost, limits their widespread adaptation. Despite this, industries use both technologies independently for different applications. To maximize the benefit of different energy storage technologies, engineers combine them as a hybrid solution. Vanadium Redox Flow Batteries (VRFB) and LiB complement each other in various aspects, and hybridization can improve power quality, improve safety, reduce cost, and make them useful for a wide range of applications. Engineers can perform hybridization at the DC level or integrate the batteries at the AC level, which requires the architecture of individual battery technologies.

[0004] Lithium batteries store energy in solid state electroactive species. A single cell voltage typically ranges from 3–4.2 volts for LNMC (lithium-nickel-manganese-cobalt) and 2–3.6 volts for Lithium Iron Phosphate ($LiFePO_4$ / LFP) during discharge and charge, respectively. The cells are connected in series and parallel to meet the DC bus voltage of the DC / AC bidirectional converter. As individual cells store the energy, unlimited series connection of cells or modules is

possible to achieve a very high DC bus voltages. However, for low power systems deployed with lithium batteries, or State of Charge (SOC) balancing of the individual modules in large system, some solutions come with DC-DC converter connected to each battery module. Use of DC–DC for each module, enables them to easily balance the SOC variation as well as allow the potential to use battery packs of various aging, even allowing second life batteries to connect.

[0005] Flow battery architecture typically involves a pair (or pairs) of tanks including those of electrolyte species, which is circulated by means of pumps to the stack module(s), where charge and discharge reaction occurs. Tank size can be varied to provide independent sizing of the energy capacity. The stack modules can be connected in series and / or parallel to match the voltage of power converter. For industrial applications requiring 100s of kW of power, a DC bus voltage of ~500 V is required to generate three phase voltage of 400 V or equivalent, based on country specific requirements. A vanadium redox flow battery cell voltage ranges between 1 volt to 1.6 volt, and this requires a large number (e.g. > 10 stacks for a stack containing 40 cells) of stack to be connected in series.

[0006] However, flow battery using electrically conductive electrolyte suffers from serious losses and degradation of series connected stacks arising from the voltage propagation in the balance of the plant, often referred as shunt current losses.

[0007] **Problem / Solution**: Hence, most of the flow batteries are designed with intermediate DC–DC converter to boost the low DC voltage to high voltage DC to match the DC voltage for the DC/AC bidirectional converter. This intermediate step converters results in poor roundtrip efficiency of VRFB. Some manufacturers are looking into series connection of large number of stacks, in which stacks are fed with the electrolyte from multi pair of tanks, which are hydraulically disconnected. This eliminates the necessity of using DC–DC converter and improves the round-trip efficiency of VRFB, however, such architecture suffers from SOC imbalance between multi tank pairs.

[0008] Existing solutions providing for charge balancing are also listed but they have their own drawbacks. For example, WO 2020/030762 A1 / PCT/EP2019/071372, titled 'Flow Battery and a method for balancing the SOC' provides for balancing the SoC, but one issue in implementation is that DC–DC

connect at each cluster, is cumbersome and costs a lot. Similarly, WO 2021/025925A1/ PCT/US2020/044075 titled 'Redox Flow Battery Arrays and Methods for State of Charge Balancing' provides for a balancing method but it too suffers from the same drawback of large size and costs. Similarly, US2019318116, titled 'Flow Battery and a method for balancing the SOC'; WO/2022/146059 / PCT/KR2021/020230 titled, 'High voltage type redox flow battery comprising SOC balancing device'. However, all such solutions have the same drawback that the implementation is extremely costly and the setup is huge.

[0009] Definitions used in this patent document are collated and provided in this section, i.e. in the background only. However, these are used across the patent and are not limited to just the background. They are applicable throughout the present specification.

[0010] **Stack**: A group of single cells constituting together as stack belonging to same technology of Battery energy storage (for example vanadium redox flow battery (VFRB), Lithium Ion, Sodium Ion, Lead Acid etc.).

[0011] **Cluster or string**: A single such stack may be considered as a CLUSTER or a group of such stacks connected in series and/or in parallel electrically is referenced as a CLUSTER as well.

[0012] If the Cluster consists of cells based out of Vanadium Redox Flow technology, then, all the cells within the cluster have same electrolyte fed to each of these cells from a common tank pair.

[0013] Different Vanadium Based Clusters have their own individual electrolyte tanks, hence forming a Multi-Tank System. The electrolytes from a common tank pair do not interact with electrolyte from tank pair/pairs.

[0014] DC–DC Converter: A power conversion system which converts one DC voltage level fed as input to equal/unequal DC voltage level as output of the power conversion system.

[0015] DC–AC Converter: A power conversion system which converts DC Voltage level to AC Voltage level and vice versa as well depending on the mode of operation of the power conversion system.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] **FIG. 1A.** depicts a typical stack including battery cells connected in series and cluster/string including multiple stacks in series;

[0017] **FIG. 1B.** depicts a manner in which state of charge can be controlled using the power management embodiment described herein;

[0018] **FIG. 2** is an introduction of a DC-DC converter between the two clusters, where each cluster is a VRFB system with an individual tank pair;

[0019] **FIG. 3** shows architecture / schematic of a hybrid energy storage system or a power flow management system;

[0020] **FIG. 4** is DC Microgrid Architecture with different Battery Energy Storage Technology connected in parallel via a DC–DC Converter;

[0021] **FIG.5** is a V-I Curve for a DC–DC Droop Control wherein the Droop Co-efficient/slope is higher i.e. less sensitive allowing more DC voltage sway in the Microgrid.

[0022] **FIG. 6** is a V-I Curve for a DC–DC Droop Control wherein the Droop Co-efficient/slope is lower i.e. more sensitive allowing less DC voltage sway in the Microgrid;

[0023] **FIG. 7** depicts an AC Microgrid Architecture with different Battery Energy Storage Technology connected in parallel via DC–AC Converter with a transformer;

[0024] **FIG. 8** depicts an AC Microgrid Architecture with different Battery Energy Storage Technology connected in parallel via DC–AC Converter without a transformer;

[0025] **FIG. 9** depicts a F-P Curve for a DC–AC Droop Control wherein the Droop Co-efficient/slope is higher i.e. less sensitive allowing more frequency sway in the Microgrid;

[0026] **FIG. 10** depicts F-P Curve for a DC–AC Droop Control. Droop Co-efficient/slope is lower i.e. more sensitive allowing less frequency sway in the Microgrid;

[0027] **FIG. 11A** and **FIG. 11B** are a flow chart and state diagram of the embodiments described herein for the state of charge, flow regulator, and controller; and

[0028] **FIG. 12A, FIG. 12B** and **FIG. 12C** together show the steps taken for implementing the balancing of state of charge in a multi-battery system.

SUMMARY

[0029] In systems having more than one flow battery units and more than one lithium batteries or similar technologies, when connected to common DC bus for the power flow through a common power converter system, SOC varies within flow battery and between lithium batteries. This creates a deficiency in the rated power of the hybrid solution limiting to inability of supplying power to rated load continuously. A small-scale DC power converter is used to work in droop control mode to enable charging or discharging of the individual DC clusters to balance the SOC during both charging and discharging. This is a simple and low-cost method without needing to disconnect clusters from the power flow. Integration of VRFB and lithium battery together to control is also disclosed.

DETAILED DESCRIPTION OF THE INVENTION

[0030]Two methods are disclosed to address the problem regarding efficiency. In one, a method of balancing SOC of multi tank (or container) VRFB system for AC coupled hybridization is provided and in another a droop control method during charge and discharge of hybrid ESS consisting of VRFB and a LiB for DC couple hybridization is provided. The efficiency issue occurs because most of the flow batteries are designed with intermediate DC–DC converter to boost the low DC voltage to high voltage DC to match the DC voltage requirement of the DC/AC bidirectional converter. This intermediate step converters results in poor roundtrip efficiency of the VRFB. One possible way to overcome the said problem is by connecting large number of stacks, in which stacks are fed with the electrolyte from multi pair of tanks, which are hydraulically disconnected. This eliminates the necessity of using DC–DC converter and improves the round-trip efficiency of VRFB, however, such architecture suffers from SOC imbalance between multi tank pairs. It is this state of charge imbalance that is sought to be addressed by the disclosed embodiments. Thus, the embodiments described herein are counter to what the others are doing and hence is in a sense contrary (tanks being hydraulically connected) to what is done in the prior art.

[0031] **FIG. 1** shows balancing SOC of multi tank VRFB stack including battery cells connected in series and cluster/string including multiple stacks in series. Each cluster may include 1-12 stacks in series.

[0032] **FIG. 1B.** depicts a manner in which state of charge can be controlled using the power management embodiment described herein. **FIG. 1B** is a schematic of a hybrid energy storage system or a power flow management system, involving two different battery technologies (Cluster-1 and Cluster-2) and a common injection/extraction point for power. In **FIG. 1B**, Cluster-1 & Cluster-2 represent two distinct energy storage clusters such as different battery types, Lithium-ion and / or Flow batteries. A DC-to-DC converter manages the voltage and current between the two clusters and acts as a controller. Injection/Extraction Point of Power is where power is either supplied to or taken from the system. It could be connected to a grid, a load, or another energy system all together. In FIG. 1B, the lines represent electrical connections, with black lines indicating standard connections and red lines with arrows indicating specific power flow directions.

[0033] With reference to **FIG. 2-5**, the following parameters are described as A = Net Injection power from the high voltage (HV) link formed by series of two Clusters, B = Injection/Extraction current, controlled using the DC-DC converter, C = Net Power Flow into Cluster-1, D = Net power Flow into Cluster-2, V1 = Primary Stack Voltage, V2 = Secondary Stack Voltage.

[0034] The DC-DC converter is operated in current control mode on the low voltage (LV) side, where the current command B is calculated from the below mentioned embodiment. The DC-DC converter is connected to either include the full cluster at LV side or it is connected to individual stacks in a cluster. The rating of the DC-DC is sourced accordingly. If SOC balancing is done at lower imbalance window, say 5-10% of variation between two clusters, even a DC-DC converter of small power rating will suffice. Although, the balancing process is done both during charging or discharging cycle but preferred only during charging cycle.

[0035] The net injection from the HV side is governed by the same controller or a different physical controller whose scope of control is to regulate the net input power/current into the system. This controller ensures that the net injection

doesn't exceed the sum of individual clusters power requirement or current requirement.

[0036] A controller for regulating power, discharge flows, and monitoring battery temperature is a part of the Lithium-Ion Battery. The Controller regulates the flow of current / voltage / heat etc. and safety precautions needed to ensure that the operating conditions of the lithium battery are kept in between the safety limits, because of the high reactivity of Lithium-Ion Batteries

[0037] The process gets the maximum charge power permissible for each individual cluster say X, Y for cluster-1 and cluster-2 respectively.

[0038] **FIG. 2** is a simplified representation of a more complex system and provides the basic architecture and power flow concepts. FIG. 2 depicts an embodiment showing power flow between Cluster-2 and the DC–DC converter is measured in amperes (current), while all other power flows are measured in kilowatts (power). This indicates that the DC-DC converter is handling current regulation for Cluster-2. Both Cluster-1 and Cluster-2 have direct connections to the injection/extraction point, allowing for flexible power management. This system likely aims to leverage the strengths of different battery technologies (e.g., high energy density of Li-ion in Cluster-1, long duration storage of flow batteries in Cluster-2) for improved performance and efficiency.

[0039] In this embodiment, for charging, power could be injected at the injection/extraction point, flowing to both clusters, with the DC-DC converter regulating the charging current for Cluster-2 and for discharging, power could be extracted from both clusters, with the DC-DC converter managing the power output from Cluster-2. For Load Balancing/Optimization, the DC–DC converter may be used to optimize the power flow between the two clusters, ensuring efficient operation and extending the lifespan of the batteries. Thus, the hybrid energy storage system with a DC-DC converter for power management, highlighting the types and units of power flow at different points in the system in FIG. 2.

[0040] **FIG. 3** is another embodiment of the present invention and is a schematic of a hybrid energy storage system or a power flow management system involving two different battery technologies (Cluster-1 and Cluster-2) and a common

injection/extraction point for power. Cluster-1 & Cluster-2: These represent two distinct energy storage clusters, different battery types like Lithium-ion and Flow batteries. A DC-to-DC converter manages the voltage and current between the two clusters. Injection/Extraction Point of Power: This is where power is either supplied to or taken from the system where the same could be connected to a grid, a load, or another energy system all together.

[0041] **FIG. 4**, like **FIG. 2** and **FIG. 3**, depicts a generalized hybrid energy storage system architecture, illustrating how multiple different battery clusters can be integrated and managed through individual DC–DC converters to a common power injection/extraction point. In the embodiment of **FIG. 4**, each battery cluster is connected to its dedicated DC-DC converter. This signifies individual control and management of each battery cluster's charging and discharging. Each DC–DC converter is connected to the power injection/extraction point. This indicates that the power flow from each cluster is managed through its respective DC-DC converter. Each battery cluster is also directly connected to the power injection/extraction point. This suggests that some battery clusters have the ability to directly supply or receive power, bypassing the DC–DC converter. Thus, the control is granular rather than centralized and hence the system is scalable and is a modular hybrid energy storage system. The use of individual DC–DC converters for each battery cluster allows for independent control and optimization of each technology, maximizing the overall system performance.

[0042] In the embodiments as described in **FIG. 2–4**, the system accommodates various battery technologies and can be easily scaled by adding more clusters; there is Individual Control, where each battery cluster is managed independently through its DC–DC converter, allowing for optimized charging/discharging based on the specific characteristics of each technology. The embodiments of FIG. 2–4 provides a high-level overview of a generalized hybrid energy storage system architecture with multiple battery clusters, each managed by its own DC–DC converter, connected to a common power injection/extraction point. It highlights the flexibility, scalability, and individual control capabilities of such systems. Bypass availability but yet connected to the other clusters: where there is a direct connection from the battery clusters to the power injection/extraction point for

certain operational modes, improving efficiency. The embodiments described in **FIG. 2–4** provide for multiple advantages: This architecture leverages the strengths of different battery technologies, creating a more robust and efficient energy storage solution and the same can be used in Grid-scale energy storage: To provide grid stability, frequency regulation, and renewable energy integration. Microgrids: To ensure reliable power supply in remote or off-grid locations. Electric vehicle charging stations: To manage high power demand and optimize charging times.

[0043] Functioning of the DC-DC converter as controller along with SOC measuring, regulator: When the power demand of cluster 1 is greater than cluster 2, the controller checks if the injection power is greater than the cluster-2 charging requirement. If this condition is true, the system enters a loop where the current command is calculated by continuously checking if the difference between D and Y is greater than 500W to trigger a protective action and avoid overcharging. If the condition holds, command B current is determined by dividing the difference between D and Y by voltage V2, which dictates how much current should be taken from the LV side and transferred to the HV side by the controller. A 5-second delay is added for the current command to reach the desired set point, and the loop continues to recheck the conditions. If the condition does not hold, no action is taken. When the power demand of cluster 1 is less than cluster 2, controller checks if the injection power is greater than the cluster-1 charging requirement. If this condition is true, the system enters a loop where the current command is determined by continuously checking if the difference between C and X is greater than 500W, triggering a protective action to avoid overcharging. In this case, command B current is negative, meaning the DC-DC converter is instructed to take power from the HV side and send it to the LV side. A 5-second delay is added for the current command to reach the desired set point, and the loop continues to recheck the conditions. If the condition does not hold, no action is taken. When the power demand of cluster 1 equals cluster 2, no action is taken, as no adjustment is necessary.

[0044] This method is simple to implement and use of small DC-DC converter pushes the power from the cluster having high SOC to cluster having low SOC.

The balancing can be active (continuous) or triggered when a difference is SOC between two cluster system is exceeding the set limit. It is recommended to balance the SOC when the difference in SOC between two cluster is below 10%, which in turn allows the size of the DC–DC to be of low power rating.

[0045] Further, the solution provided herein is mostly DC-DC conversion before going to DC-AC converters. Hence the architecture as provided by way of embodiments / processes described herein is fundamentally different than what is disclosed earlier.

[0046] The method proposed in the patent applications described herein use MOSFET switches to disengage some of the stack from the cluster. The existing solution requires multiple DC-DC at each cluster.

[0047] Detailed process flow in terms of system commands is described in **FIG. 12A** and **12A1 and 12B.**

[0048] **Droop control method during charge and discharge of hybrid ESS consisting of VRBs and a LIBs for DC and AC coupled hybridization.**

[0049] The droop strategy as described herein is a cooperative control scheme and controls the delivered amount of power or current based on voltage drop across a particular load type. Conventionally, in DC droop control methods, a source is controlled to linearly decrease DC output voltage, as the DC output current increases; and generators can be controlled either using a current-mode or a voltage-mode droop control scheme.

[0050] **FIG. 4** is a case of a DC/AC Microgrid that is formed by VRFB Energy storage technology along with different battery energy storage technology connected on the DC/AC-Microgrid.

[0051] Conventional DC/AC-Microgrid usually have a Master Source which regulates the DC Bus Voltages/ AC Bus frequency and act as a Slack Bus for absorbing or delivering any power changes on the DC-Bus/AC-Bus, while other sources (even with same battery technology) work as a slave which absorb or deliver power to the DC/AC Microgrid based on the decision given by implemented Controller. This way of Master Slave control demands the Master Source to be sized enough such that it can absorb/deliver the max step change possible on the DC/AC-Microgrid before the controller can allocate new references to each of other

conversion system connected to each cluster. The Failure of this Master in the DC/AC-Microgrid leads to failure/collapse of the entire Microgrid.

[0052] The solution provided by the embodiment herein is to introduce Multi-Masters in the DC/AC-Microgrid network which work together in unison to share power based on the later mentioned control structure / methodology and also regulate the (DC-Microgrid voltage/AC- Microgrid Voltage and Frequency) between the permissible voltage bandwidth in case of DC-Microgrid and permissible Frequency Bandwidth in case of AC-Microgrid.

[0053] The embodiment described herein eliminates the need to oversize a particular Energy Storage element in the network hence improving the usability of the power rating of batteries substantially.

[0054] The embodiment described herein increases the reliability of the DC/AC-Microgrid as failure of any Energy storage element in the DC-Microgrid still keeps the Microgrid Alive with a reduced overall power rating. This is represented in **FIG. 6** as the slope of current reduces because of the Controller, Regulator working in accordance with the embodiments as described herein.

[0055] The embodiment described herein actively manages the charging power for each of the energy storage element to avoid overcharging based on the SOC dynamically hence enabling overcharge protection without switching off the battery as depicted in.

[0056] Control Methodology: Each of the DC-DC Converter which converts i.e. step ups or step downs the Cluster Voltage to a regulated output is connected to each of battery energy storage unit. The individual clusters may or may not be of the same power rating but is within the operation range of the DC–DC Converter. There is a controller which controls the droop coefficient, the DC–Voltage reference level and current limit level of each of the DC–DC Converter in the Microgrid. The cluster readiness status is continuously monitored by the controller to enable start/stop control of the DC-DC Converter. The N cluster in the Microgrid have $X_1, X_2 \ldots, X_N$ Watts as the charging requirement. This charging requirement is generated by a charge management process / method which works based on SOC of the individual clusters. The Charging power is sorted in Descending order. In this particular case it $X_1 > X_2 > X_3 > \ldots > X_N$. This also directly implies that SOC_1

< SOC_2 < SOC_3 < . . . < SOC_N. Then its referenced to X_1. Making it: $1 > \frac{X2}{X1} > \frac{X3}{X1} > \frac{X4}{X1}$ > . . . > $\frac{XN}{X1}$. The lowest droop coefficient is allocated for the Cluster's DC-DC Converter with the highest charging requirement. The value of the lowest droop coefficient depends on the permissible voltage sway in the DC-Microgrid for example y% w.r.t to the voltage reference. Meaning the voltage is allowed to sway between Vref (1-0.01y) and Vref (1+0.01y). The remaining DC–DC Converters are allocated droop coefficient as $y*X_1/X_2$, $y*X_1/X_3$, . . . , $y*X_1/X_N$.

[0057] Whenever there is a power injection detected by the controller based on either a current sensor on the output bus or/and a power meter on the output bus of the microgrid, then Controller allocates the droop coefficient based on the above stated process / method and hence enables injection power being diverted to each clusters in the same ratio defined by the charging power required of each cluster. This control methodology enables the highest share of power being diverted to the cluster with lowest SOC in the microgrid. As an additional layer of protection, the current limits are also chosen to protect the clusters from overcharging which are calculated as below based on the charging requirement of each of the clusters $I_1 = X_1/ (V_{ref} + 0.01*y)$, $I_2 = X_2/ (V_{ref} + 0.01*y)$, . . . , $I_N = X_N/(V_{ref} +0.01*y)$.

[0058] This control methodology helps in keeping the SOC around the same range of values continuously throughout the operation period. Whenever a discharge is detected by a controller the droop coefficient are chosen as: sort the rated discharge of the individual Clusters based on power in the Microgrid. Here the rated discharge is usually constant throughout the wide range of SOC. However, at low SOC's range of each cluster, the controller may derate the rated discharge capability of the clusters. For example, for simple understanding $X_1=X_2>X_3=X_4=X_5>X_6>$.....$>X_N$. Scaling w.r.t to X_1, then $1= X_2/X_1 > X_3/X_1 = X_4/X_1 = X_5/X_1 > X_6/X_1 >$ .... $> X_N/X_1$. Allocating the lowest droop coefficient a y% to the cluster with maximum discharge capability. The droop coefficient accordingly is allocated as $y*X_1/X_2$, $y*X_1/X_3$,.....,$y*X_1/X_N$.

[0059]AC Coupled VRFB Clusters system with Three wire DC-AC Bi-directional Power Conversion System:

[0060]The droop strategy as described herein is a cooperative control scheme designed to manage the power delivery or current across various clusters in a DC-

AC microgrid system. This methodology controls the voltage drop across a particular load type, ensuring optimal power distribution based on the state of charge (SOC) and power requirements of each cluster. In conventional DC droop control methods, the source is controlled to linearly decrease the DC output voltage as the output current increases, and generators are controlled using either a current-mode or a voltage-mode droop control scheme.

[0061] **FIG. 7** illustrates a microgrid energy management system comprising multiple energy storage clusters, each integrated with an AC-DC Converter that enables bidirectional power flow between the clusters and a central Power Injection/Extraction Point. The system operates under a cooperative droop control strategy, where a controller dynamically adjusts the droop coefficient and AC frequency reference level based on real-time charging and discharging requirements, as given in the embodiment. Each cluster's charging power demand is sorted in descending order, ensuring that the cluster with the highest demand receives the lowest droop coefficient, thereby prioritizing power distribution to maintain uniform state-of-charge (SOC) levels. The DC-DC Converter facilitates charge balancing by transferring power between clusters based on voltage and charge differentials, ensuring optimal utilization of stored energy. The controller continuously monitors cluster readiness and regulates net power injection, ensuring it does not exceed the sum of individual cluster requirements while applying predefined current limits to prevent overcharging. During discharge, the system prioritizes clusters with higher rated discharge capabilities, dynamically adjusting droop coefficients and derating discharge at low SOC levels for enhanced battery longevity. The power exchange is maintained within the voltage reference limits, Fref(1-0.01y) to Fref(1+0.01y), ensuring stability and reliability. As given in the embodiment, this methodology effectively balances power distribution, optimizes energy flow, and ensures continuous microgrid stability through adaptive droop control and charge management process / method.

[0062]In the embodiment of **FIG. 8,** AC-coupled VRFB cluster system with a three-wire DC-AC bi-directional power conversion system operates based on a control methodology where each AC-DC converter is responsible for converting DC voltage to AC and vice versa, depending on the operation. The individual clusters

may have varying power ratings but remain within the operational range of the DC-AC converter. A controller governs the droop coefficient and AC frequency reference level for each DC-AC converter within the microgrid while continuously monitoring cluster readiness to enable start/stop control. The charging requirements of the clusters are determined using a charge management algorithm that sorts the charging power in descending order, implying that the cluster with the lowest state of charge (SOC) has the highest power requirement. The lowest droop coefficient is assigned to the cluster with the highest charging need, with its value determined based on the permissible voltage sway in the DC microgrid. The remaining DC-AC converters receive droop coefficients in proportion to their charging power requirements. When power injection is detected by a controller through a current sensor or power meter at the output bus, the controller allocates the droop coefficient accordingly, ensuring power is distributed among clusters in the same ratio as their charging requirements. This methodology ensures that the cluster with the lowest SOC receives the highest share of power, maintaining the SOC across the microgrid within a balanced range during operation. During discharge, the droop coefficients are allocated based on the sorted discharge power ratings, with the lowest droop coefficient assigned to the cluster with the highest discharge capability. If a cluster's SOC reaches a low threshold, the controller may derate its discharge capability. This dynamic droop control mechanism enables effective power distribution among multiple battery clusters in the microgrid while ensuring optimal charge balancing across clusters .

[0063] The setup of the controller with the microgrid, ensures a P/F slope as shown in **FIG.9** having balanced power distribution among clusters within the microgrid, with the droop coefficient allocated dynamically. The AC-DC converters adjust their output frequency within permissible voltage sway limits, maintaining system stability while ensuring that power is diverted according to the charging or discharging requirements of each cluster, as determined by the controller and charge management method/ process.

[0064] **FIG.10** illustrates the P/F slope where droop control method in a DC-AC microgrid is used as described in FIG. 3/4, where the droop coefficient and AC

frequency reference adjust based on the power injection or extraction needs of different battery clusters. As described in the embodiments, this ensures balanced power distribution by dynamically allocating the lowest droop coefficient to the cluster with the highest charging or discharging requirement, maintaining uniform state of charge across the system.

[0065] Control methodology: Each of the AC-DC Converter which converts DC voltage to AC Voltage form and Vice-versa depending the operation. The individual clusters may or may not be of the same power rating but is within the operation range of the DC-AC Converter. There is a controller which controls the droop coefficient and the AC-frequency reference level of each of the DC-AC Converter in the Microgrid. The cluster readiness status is continuously monitored by the controller to enable start/stop control of the DC-AC Converter. The N cluster in the Microgrid have X_1, X_2....X_N Watts as the charging requirement. This charging requirement is generated by a charge management process / method which works based on SOC of the individual clusters. The Charging power is sorted in Descending order. In this particular case it $X_1 > X_2 > X_3 > \ldots > X_N$. This also directly implies that $SOC_1 < SOC_2 < SOC_3 < \ldots < SOC_N$. Then its referenced to X_1. Making it: $1 > \frac{X2}{X1} > \frac{X3}{X1} > \frac{X4}{X1} > \ldots > \frac{XN}{X1}$. The lowest droop coefficient is allocated for the Cluster's DC-DC Converter with the highest Charging requirement. The value of the lowest droop coefficient depends on the permissible voltage sway in the DC-Microgrid for example y% w.r.t to the voltage reference. Meaning the Voltage is allowed to sway between AC frequency $F_{ref}(1-0.01y)$ and $F_{ref}(1+0.01y)$. The remaining DC-AC Converters are allocated droop coefficient as $y*X_1/X_2$, $y*X_1/X_3$,....., $y*X_1/X_N$. Whenever there is a power injection detected by the controller based on either a current sensor on the output bus or/and a power meter on the output bus of the microgrid, then Controller allocates the droop coefficient based on the above stated process / method and hence enables injection power being diverted to each clusters in the same ratio defined by the charging power required of each cluster.

[0066] This control methodology enables the highest share of power being diverted to the cluster with lowest SOC in the microgrid. This control methodology helps in

keeping the SOC around the same range of values continuously throughout the operation period. Whenever a discharge is detected by a controller the droop coefficient are chosen as: sort the rated discharge of the individual Clusters based on power in the Microgrid. Here the rated discharge is usually constant throughout the wide range of SOC. However, at low SOC's range of each cluster, the controller may derate the rated discharge capability of the clusters. For example, for simple understanding $X_1 = X_2 > X_3 = X_4 = X_5 > X_6 > \ldots > X_N$. Scaling w.r.t to X1, then $1 = X_2 / X_1 > X_3 / X_1 = X_4 / X_1 = X_5 / X_1 > X_6 / X_1 > \ldots > X_N / X_1$ Allocating the lowest droop coefficient, a y% to the cluster with maximum discharge capability. The droop coefficient accordingly is allocated as $y*X_1 / X_2$, $y*X_1/X_3, \ldots, y*X_1/X_N$.

[0067] **FIG. 11A** and **FIG. 11B** are a flow chart and state diagram of the embodiments described herein for the state of charge, flow regulator, and controller. **FIG. 12A, FIG. 12B** and **FIG. 12C** together show the steps taken for implementing the balancing of state of charge in a multi-battery system.

Embodiments

[0068] Embodiment 1. An embodiment of balancing a state of charge of electrolytes in a battery system having a plurality of flow battery stacks in series and supplied with electrolytes from at least two different sources, the stacks each having a plurality of cells, the embodiment comprising:

a series of flow battery stacks divided into at least a plurality of clusters having a primary stack voltage **V1** and a secondary stack voltage **V2**;

determining a net power flow across one of the plurality as **C**, and across the other as **D** and a difference across the at least a plurality of clusters;

determining a net injection current **A** from a **HV** link formed by the at least plurality of clusters in series;

determining an injection or an extraction current **B** using a DC-DC converter;

wherein maximum charge power permissible for each individual cluster for the at least one of clusters, is **X** and **Y**, and

charge is balanced by DC–DC converter taking power from the lower voltage side and transferring to high(er) voltage side, based on a positive determination of ratio of **D-Y / V2**,

charge is balanced by DC–DC converter taking power from the higher voltage side and transferring to low(er) voltage side, based on a determination of ratio of – **(C-X / V2)**, and

taking no action if X = Y.

[0069] 2. The embodiment 1, wherein the DCDC converter determines both the ratios during charging or discharging cycles.

[0070] 3. The embodiment 1, wherein the balancing is done in charging cycle.

[0071] 4. The embodiment 1, wherein the net injection from the **HV** side is by a controller which regulates the net input power / current into the system and wherein the net injection does not exceed the sum of individual clusters' power requirement or current requirement.

[0072] 5. The embodiment 1 wherein a delay of 5 seconds is added post determination of the ratios for balancing of charge in the system.

[0073] 6. The embodiment 1, wherein the balancing a state of charge of electrolytes is either active (continuous) or triggered upon a difference in state of charge being beyond a threshold.

[0074] 7. The embodiment of para [0072], wherein the balancing a state of charge of electrolytes between the two clusters is done when the difference between the two clusters is below 10%.

[0075] Embodiment 2. A embodiment of droop control in a DC-AC microgrid, formed by Vanadium Redox Flow Battery (VRFB) energy storage technology along with different battery energy storage technology connected on the DC/AC-microgrid having multiple clusters, the method comprising:

a controller configured to:

control a droop coefficient, a DC-Voltage reference level (y) and a current limit level of each of a plurality of DC-DC Converters in the microgrid; and

continuously monitor cluster readiness status to enable start/stop control of the plurality of DC-DC Converters;

wherein clusters in the microgrid have $X_1, X_2, \ldots, X_N$ Watts as a charging requirement and the charging requirement is generated by a charge management process which works based on system of charge (SOC) of the individual clusters by;

sorting charging power in descending order $X_1 > X_2 > X_3 > \ldots > X_N$ such that $SOC_1 < SOC_2 < SOC_3 < \ldots < SOC_N$;

referencing the sorted charging power by referencing X_1 as $1 > \frac{X2}{X1} > \frac{X3}{X1} > \frac{X4}{X1} > \ldots > \frac{XN}{X1}$; and

allocating a lowest droop coefficient as determined for a cluster's DC-DC converter having the highest charging requirement, wherein the value of the lowest droop coefficient depends on the permissible voltage sway in the microgrid as a percentage with respect to the voltage reference (y) between $V_{ref.}$ (1-0.01y) and $V_{ref.}$ (1+0.01y), such that

power is diverted to each clusters in the same ratio defined by charging power required of each cluster; and

highest share of power is diverted to the cluster with lowest state of charge in the microgrid.

[0076] 9. The embodiment 2, wherein remaining DC-DC Converters are allocated droop coefficient as $y*X_1/X_2, y*X_1/X_3, \ldots, y*X_1/X_N$.

[0077] 10. The embodiment 2, wherein current limits are pre-selected to protect the clusters from overcharging and calculated based on the charging requirement of each of the clusters as

$I_1 = X_1/ (V_{ref} + 0.01*y)$,

$I_2 = X_2/ (V_{ref} + 0.01*y), \ldots,$

$I_N = X_N/(V_{ref} +0.01*y)$

[0078] Embodiment 3. A embodiment of droop control in a DC-AC microgrid, formed by Vanadium Redox Flow Battery (VRFB) energy storage technology along

with different battery energy storage technology connected on the DC/AC-microgrid having multiple clusters, the method comprising:

a controller configured to:

control a droop coefficient, a DC-Voltage reference level (y) and a current limit level of each of a plurality of DC-DC Converters in the microgrid; and

continuously monitor cluster readiness status to enable start/stop control of the plurality of DC-DC Converters;

wherein clusters in the microgrid have $X_1, X_2, \ldots, X_N$ Watts as a charging requirement and the charging requirement is generated by a charge management process which works based on system of charge (SOC) of the individual clusters by;

sorting charging power in descending order $X_1 > X_2 > X_3 > \ldots > X_N$ such that $SOC_1 < SOC_2 < SOC_3 < \ldots < SOC_N$;

referencing the sorted charging power by referencing X_1 as $1 > \frac{X2}{X1} > \frac{X3}{X1} > \frac{X4}{X1} > \ldots > \frac{XN}{X1}$; and

allocating a lowest droop coefficient as determined for a cluster's AC-DC converter having the highest charging requirement, wherein the value of the lowest droop coefficient depends on the permissible voltage sway in the microgrid as a percentage with respect to the voltage reference (y) with AC frequency between $F_{ref.}$ (1-0.01y) and $F_{ref.}$ (1+0.01y), such that

power is diverted to each clusters in the same ratio defined by charging power required of each cluster;

highest share of power is diverted to the cluster with lowest state of charge in the microgrid; and

the state of charge remains in a same range of values continuously throughout the operation period.

[0079] 12. The embodiment of droop control according to claim 11, wherein remaining AC-DC Converters are allocated droop coefficient as $y*X_1/X_2$, $y*X_1/X_3$, . . . , $y*X_1/X_N$.

[0080] It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes will be suggested in view thereof to those skilled in the art and will be included in the essence and scope of this application.

[0081] While the present invention has been shown and described in connection with the exemplary embodiments, it will be apparent to those skilled in the art that modifications and variations can be made without departing from the spirit and scope of the invention as defined by the appended claims.

* * *

CLAIMS

We Claim:

1. A method of balancing a state of charge of electrolytes in a battery system having a plurality of flow battery stacks in series and supplied with electrolytes from at least two different sources, the stacks each having a plurality of cells, the method comprising:

a series of flow battery stacks divided into at least a plurality of clusters having a primary stack voltage **V1** and a secondary stack voltage **V2**;

determining a net power flow across one of the plurality as **C**, and across the other as **D** and a difference across the at least a plurality of clusters;

determining a net injection current **A** from a **HV** link formed by the at least plurality of clusters in series;

determining an injection or an extraction current **B** using a DC-DC converter;

wherein maximum charge power permissible for each individual cluster for the at least one of clusters, is **X** and **Y**, and

balancing charge by the DC-DC converter:

taking power from the lower voltage side and transferring to high(er) voltage side, based on a positive determination of ratio of **D-Y / V2**, or

taking power from the higher voltage side and transferring to low(er) voltage side, based on a determination of ratio of – **(C-X / V2)**, and

taking no action if X = Y;

wherein in a condition where maximum charge power permissible for each individual cluster for the at least one of clusters **X** is greater than maximum charge power permissible for another cluster **Y**, wherein when

the injection current **A** is greater than the cluster-2 charging requirement, **A > Y**,

charge is balanced by the DC-DC converter taking power from the lower voltage side and transferring to high(er) voltage side, based on a positive determination of ratio of **D-Y / V2**,

taking no action if X = Y;

wherein in a condition where maximum charge power permissible for each individual cluster for the at least one of clusters **X** is greater than maximum charge power permissible for another cluster **Y**, wherein when the injection current **A** is greater than the cluster-1 charging requirement, **A > X**,

charge is balanced by the DC-DC converter taking power from the higher voltage side and transferring to low(er) voltage side, based on a determination of ratio of – **(C-X / V2)**,

taking no action if X = Y.

2. The method of claim 1, wherein the DC-DC converter determines both the ratios, **D-Y / V2** or – **(C-X / V2)**, during charging or discharging cycles.

3. The method of claim 1, wherein balancing of charge is done in a charging cycle.

4. The method of claim 1, wherein the net injection from the **HV** side is by a controller which regulates the net input power / current into the system and wherein the net injection does not exceed the sum of individual clusters' power requirement or current requirement.

5. The method of claim 1 wherein a delay of 5 seconds is added post determination of the ratios for balancing of charge in the system.

6. The method of claim 1, wherein the balancing a state of charge of electrolytes is either active (continuous) or triggered upon a difference in state of charge being beyond a threshold.

7. The method of claim 6, wherein the balancing a state of charge of electrolytes between the two clusters is done when the difference between the two clusters is below 10%.

8. A method of droop control in a DC-AC microgrid, formed by Vanadium Redox Flow Battery (VRFB) energy storage technology along with different battery energy storage technology connected on the DC/AC-microgrid having multiple clusters, the method comprising:

a controller configured to:

control a droop coefficient, a DC-Voltage reference level (y) and a current limit level of each of a plurality of DC-DC Converters in the microgrid; and

continuously monitor cluster readiness status to enable start/stop control of the plurality of DC-DC Converters;

wherein clusters in the microgrid have $X_1, X_2, \ldots, X_N$ Watts as a charging requirement and the charging requirement is generated by a charge management process which works based on system of charge (SOC) of the individual clusters by;

sorting charging power in descending order $X_1 > X_2 > X_3 > \ldots > X_N$ such that $SOC_1 < SOC_2 < SOC_3 < \ldots < SOC_N$;

referencing the sorted charging power by referencing X_1 as $1 > \frac{X2}{X1} > \frac{X3}{X1} > \frac{X4}{X1} > \ldots > \frac{XN}{X1}$; and

allocating power to a cluster on either of:

determination of a lowest droop coefficient for a cluster's DC-DC converter having the highest charging requirement, wherein the value of the lowest droop coefficient depends on the permissible voltage sway in the microgrid as a percentage with respect to the voltage reference (y) between $V_{ref.}$ (1-0.01y) and $V_{ref.}$ (1+0.01y), OR

determination of a lowest droop coefficient as determined for a cluster's AC-DC converter having the highest charging requirement, wherein the value of the lowest droop coefficient depends on the permissible voltage sway in the microgrid as a percentage with respect to the voltage reference (y) with AC frequency between $F_{ref.}$ (1-0.01y) and $F_{ref.}$ (1+0.01y),

diverting power to each of the clusters in a same ratio defined by charging power required of each cluster; wherein highest share of power is diverted to the cluster with lowest state of charge in the microgrid; and

state of charge remains in a same range of values continuously throughout the operation period.

9. The method of claim 8, wherein remaining DC-DC Converters are allocated droop coefficient as $y*X_1/X_2$, $y*X_1/X_3$, . . . , $y*X_1/X_N$.

10. The method of claim 8, wherein current limits are pre-selected to protect the clusters from overcharging and calculated based on the charging requirement of each of the clusters as

$I_1 = X_1/ (V_{ref} + 0.01*y)$,

$I_2 = X_2/ (V_{ref} + 0.01*y)$, . . . ,

$I_N = X_N/(V_{ref} +0.01*y)$

11. The method of claim 10, wherein remaining AC–DC Converters are allocated droop coefficient as $y*X_1/X_2$, $y*X_1/X_3$, . . . , $y*X_1/X_N$.

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