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CIGRE US National Committee
2017 Grid of the Future Symposium

Advanced Lead Acid Batteries for Grid Storage as Stationery Energy Source

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SUMMARY

One of the remarkable changes happening in the beginning of this century is the transition from fossil fuel energy sources to renewable energy, and moving away from the centralised power centres to distributed generation. As these ideas are increasingly being adopted, there is a challenge to coordinate the availability of electricity with electrical loads. The battery energy storage system is a rugged and reliable facilitator in adopting renewable energy. This technology relieves instantaneous imbalances between renewable generation and load demand. It serves this purpose by storing electrical energy and then discharging it when solar or wind sources are not available, thereby eliminating the unpredictability. Of the various types of battery technologies currently available, Li-ion and Redox Flow types are prevalent. Lead acid type batteries are the oldest and most commonly used batteries, they are low-cost and adaptable to numerous uses. "Advanced Lead Acid" batteries are a hybrid of lead-acid technology with ultra-capacitors; the lead (Pb) electrode is replaced with a Pb + C electrode. This increases efficiency and lifetime of the cell and improve operation at a partial state-of-charge. This paper discusses various promises and pitfalls of advanced lead acid batteries and elaborates on a specific method to improve the efficiency of lead acid based technologies. Results of a small-scale pilot study incorporating this method are presented. The pilot study was conducted on a site with residential loads. Hybrid inverter charger systems combined with individual control systems to manage charging and discharging cycles were set up. The results were analysed by comparing data derived from a battery bank utilizing the new technique and data derived from a second bank without it.

KEYWORDS

Renewable energy; Lead Acid Batteries; Energy Storage; Cell Equalization; Cell Switching

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I. Introduction

The use of large-scale advanced lead acid (ALA) battery storage with PV and wind turbine generators allows for coordination of variable renewable energy with electricity demand. The other promising features of Battery energy storage system as described in [1, 2]:

1. Transmission Systems: Improve transmission grid performance by providing voltage support and grid stabilization; defer transmission investment and optimize transmission related to renewable sources; provide system capacity and adequacy of resources, and shift renewable generation output.
2. Peaker Replacement: Large scale energy storage system to replace peaking gas turbine facilities; use as spinning reserve and bring online quickly to meet the rapidly increasing demand for power at peak as well as quickly take offline as the power demand diminishes.
3. Distribution Substation and Feeders: Energy storage systems placed at substations and along distribution feeders are controlled by utilities to provide flexible peaking capacity while also mitigating stability problems and enhance system reliability and resiliency.
4. Frequency Regulation: Energy storage system can be designed to balance power by raising or lowering output to follow the changes in load so that system frequency is held within regulatory limits.
5. Microgrid and Island Grids: Energy storage systems support small power systems that can island or otherwise disconnect from the broader power grid, by supporting stability and reliability, as well as integrate renewable/intermittent resources.
6. Residential: Energy: Storage systems for behind-the-meter residential home use provides backup power, power quality improvements and extends usefulness of self-generation, e.g. solar plus storage. They are also used to regulate the electricity sold back to the grid from distributed PV applications.

One of the issues regarding an ALA battery bank used as an energy storage system is capacity degradation over time. Charge equalization of cells is an important factor in this regard. Most battery systems utilize multiple battery cells in series. Large scale systems use a combination of parallel and series connections to achieve expected capacity. Usually one battery charger is connected across the entire bank of cells to charge them. Although each cell is expected to charge equally, voltage variations among cells do occur. Differences in cell chemistry and normal differences during repeated cycles of cell charge and discharge lead to large non-uniformities in cell charge levels and correspondingly different cell terminal voltages [3]. The electrolyte of the battery can become stratified, causing inactive areas in the plate material. If this condition continues for extended periods, the battery plate can become unusable.

Research work on this problem include a number of techniques [3-6], notable being dynamic equalization technique using isolated flyback dc-dc converter, centralized forward converter with a multi-winding transformer, current diverter, double-tiered switched capacitor charge technique and a generalized battery management system with smart battery modules. Here a novel technique is explained to equalize-charge a series battery bank.

II. Cell switching scheme for voltage equalization

A new technique is proposed to achieve equilibrium in the cell voltages of a series of batteries. This method states that if the sequential position of battery cells in a series connected bank can be reconfigured, then the chemical activity of the changed cells will increase. More specifically, cells at the positive and negative ends of a bank of batteries are usually more active than those in the middle. After certain period of usage voltage of the middle cells tend to fall below the voltage of the cells at the two terminals. If the connection between cells is now switched in a way that the cell with lowest voltage occupies the position of the cell with the highest voltage, i.e. the cell in one of the middle slots move to the first slot after the positive terminal, then that cell will charge to a higher voltage.

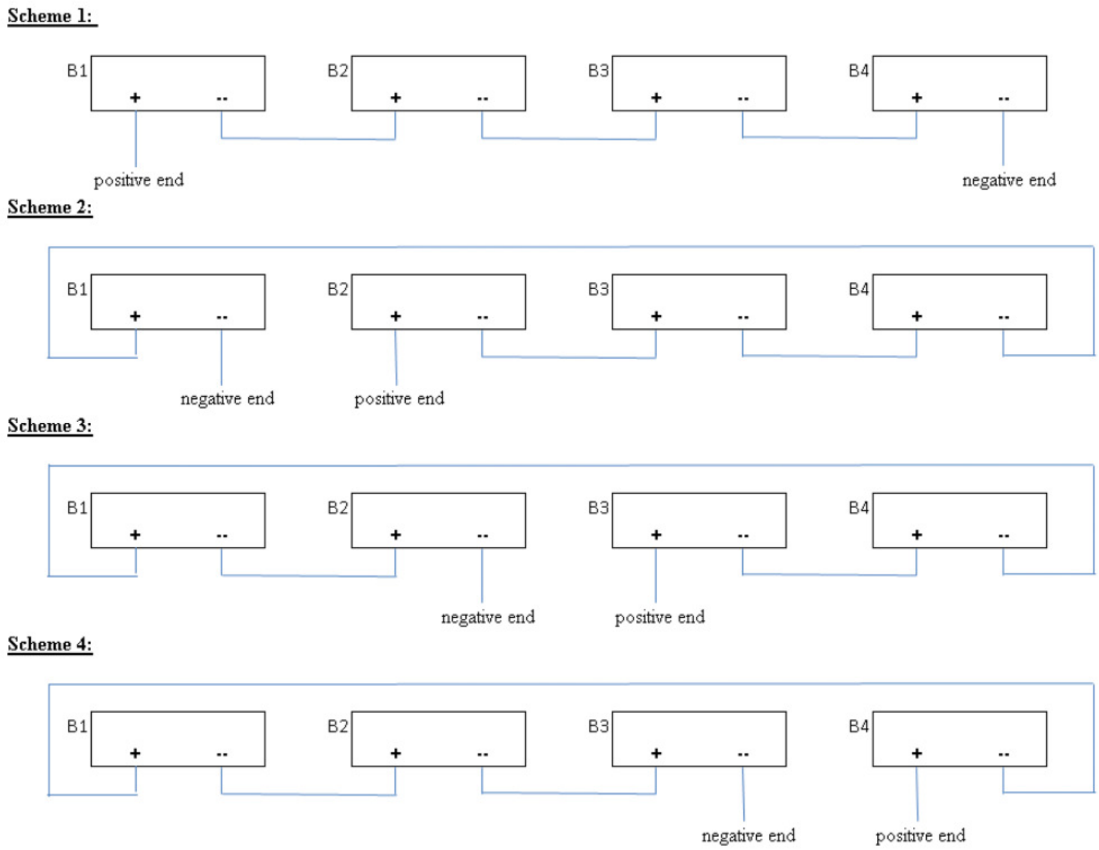

Fig. 1: Battery switching scheme for cell voltage equalization.

From Fig. 1 above, let B1, B2, B3, B4 be 4 sets of battery cells. If B1charge (voltage) is detected as lowest, it will be put in the 1st position from the positive end in scheme 1. If B2 charge is detected as lowest, it will be put in the 1st position from the positive end in scheme 2 and so on.

III. Development of control design for cell switching scheme

In contrast to existing research [4] which uses Smart Battery Modules (SBM) for a battery management system, an effort is made in this arrangement to delve into the details of the interconnection between cells and the control philosophy to achieve a flexible switching scheme. The objective is to change from one sequence of cells to another sequence that will shift the cell with lowest voltage to a more advantageous position that will enable it to get charged to a higher level.

IF $V_{B1} = \mathrm{MIN}\{V_{B1}, V_{B2}, V_{B3}, V_{B4}\}$ THEN SET $S_{W1} = 1$, RESET $S_{W2}, S_{W3}, S_{W4} = 0$;
ELSIF $V_{B2} = \mathrm{MIN}\{V_{B1}, V_{B2}, V_{B3}, V_{B4}\}$ THEN SET $S_{W2} = 1$, RESET $S_{W1}, S_{W3}, S_{W4} = 0$;
ELSIF $V_{B3} = \mathrm{MIN}\{V_{B1}, V_{B2}, V_{B3}, V_{B4}\}$ THEN SET $S_{W3} = 1$, RESET $S_{W1}, S_{W2}, S_{W4} = 0$;
ELSIF $V_{B4} = \mathrm{MIN}\{V_{B1}, V_{B2}, V_{B3}, V_{B4}\}$ THEN SET $S_{W4} = 1$, RESET $S_{W1}, S_{W2}, S_{W3} = 0$;
END_IF ;

Fig. 2: Sample of Structured Text of the control signal generating algorithm.

Safety of the battery bank as an operating unit is of prime concern while developing the control scheme. A temperature sensor is added to prevent any switching in case the ambient temperature around the battery bank rises higher than a safe limit. A reasonable time delay is added after every switch to allow the cell charge and the cell voltages to settle down before attempting another switch.

Generally, it's not necessary to have fast response by the electronic circuits, as is usually expected from power electronic devices. Instead the control concept will focus on simplifying the circuit.
Bi-directional contacts between cells will be used since the direction of current flow in the battery changes when switching from "charging" state to "discharging" state and vice versa.

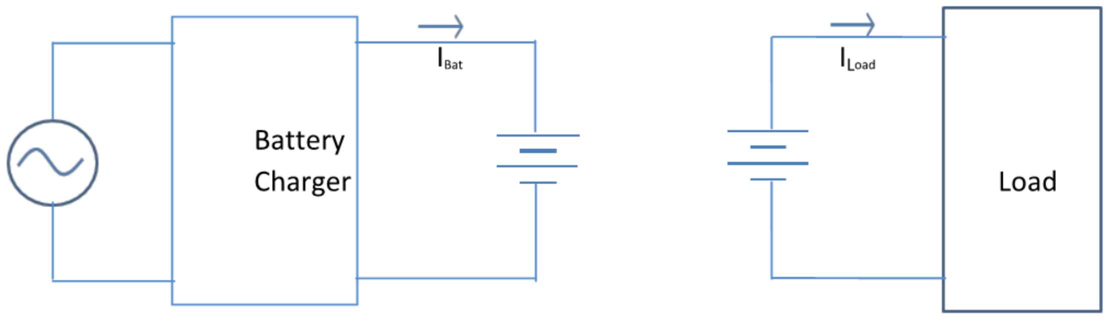

Fig. 3: Change of current direction through a battery bank.

There are several options available for the selection of a bi-directional switch to be used in between the cells, e.g. electromagnetic contactors, high current MOSFET switches etc.

A high current MOSFET-based switching device is constructed from 4 individual MOSFET components. These are configured in a standard H-bridge circuit [7]. The H-bridge can be controlled (modulated) such that current is allowed to flow in either a forward or reverse direction to the load. MOSFET are selected to have a high current rating (> 100 A) and low on-state resistance (<3 milli-Ohms). Thermal management of the MOSFETs is achieved through heat sinking designed that usually include mounting the MOSFETs to a thermally conductive substrate with passive air cooling.

A set of back-to-back MOSFET switches are selected for the test for bi-directional current flow and simplicity. The control signal of an SSR turns on the opto-coupled LED which activates a photo sensitive diode. They are more reliable than electromagnetic contactors since there are no moving parts. For higher current application heat sinks are used which are very common, for example 'mini D' and 'D' family of solid state contactors with heat sinks from Power IO [8]. A substrate diode is inherent in a MOSFET structure and has forward current, reverse voltage ratings similar to the MOSFET itself. It conducts in the reverse direction. Consequently, a single MOSFET is incapable of blocking current in both directions. For ac or dc with bi-directional operation, the two MOSFETs are connected back-to-back with the source pins connected. The drain terminals are connected to either side of the load.

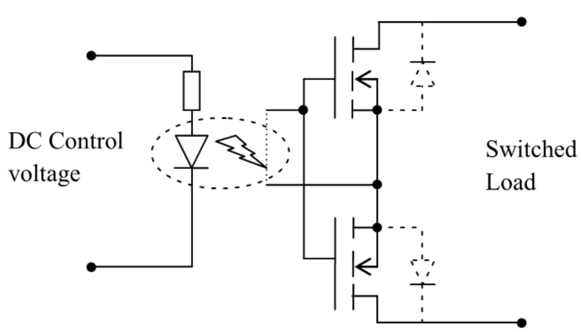

Fig. 4: Typical solid state relay with two MOSFETs connected as back-to-back switches.

When the relay is conducting, the common source connection is included in the signal level. Both MOSFET gate voltages are biased positive compared to the source potential by the optically coupled diode. A solid-state relay with opto-electric isolation and two MOSFETs joined at the source is shown in Fig. 4. The contact resistance for an SSR is greater [9] because the electrical circuit is connected through a transistor instead of a metal connective element, as is done using electromechanical relays. SSRs are not as robust as electromechanical relays. They are susceptible to transient currents and damage when operated above the device rating.

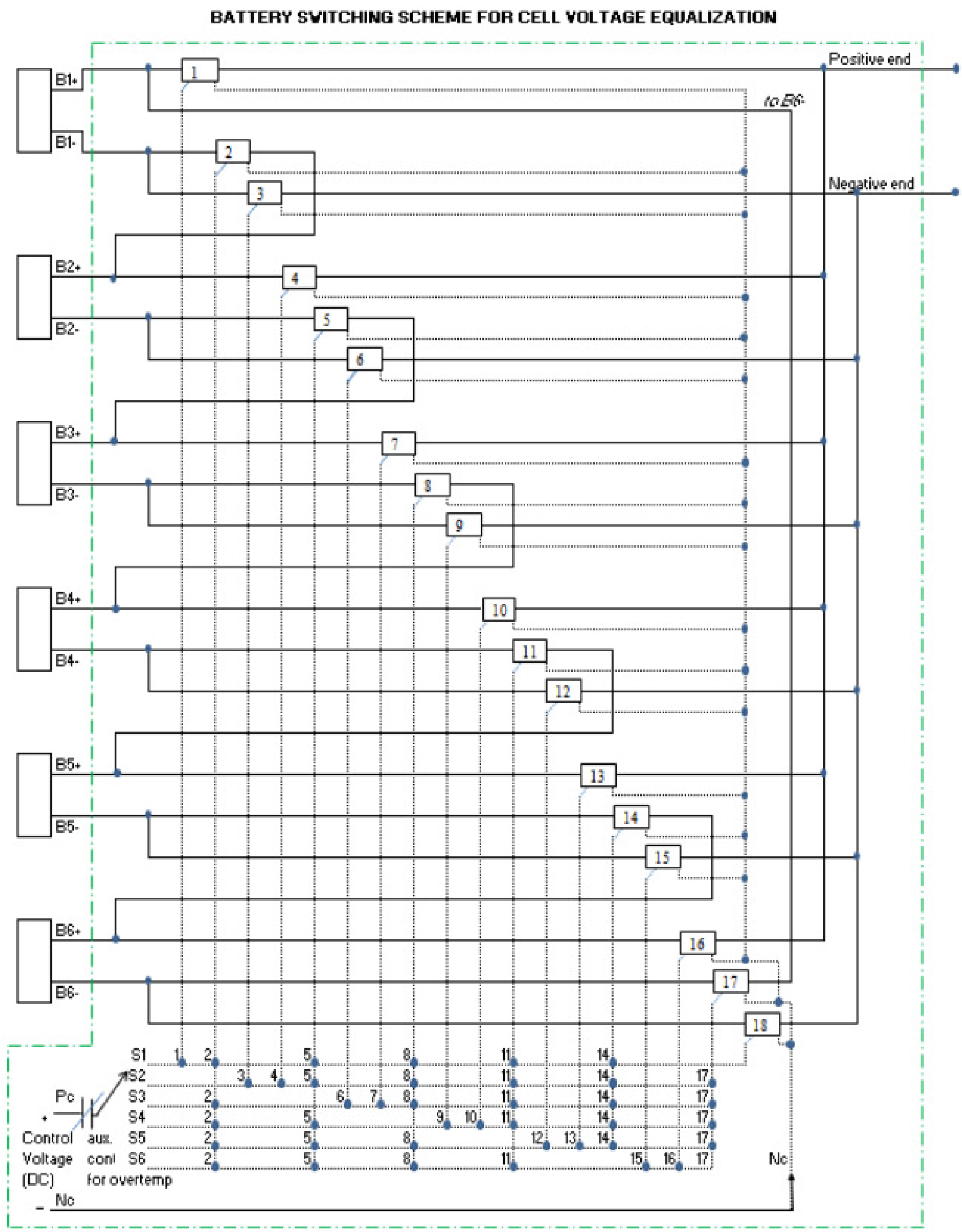

Fig. 5: Control circuit for battery cell switching scheme.

IV. Control circuit diagram for cell switching scheme

The circuit diagram in Fig. 5 details the basic control concept where the battery bank is assumed to be 6 series connected cells with nominal value of 2 V each. Total battery bank nominal voltage is then 12 V. Each cell terminals are marked as B1+, B1-, B2+, B2- and so on. Solid state relays are used to connect between two adjacent cells. Pc and Nc are the positive and negative control voltage terminals with Nc being common for all the relays.

The initial position of control switch is assumed at S1, and the battery temperature is at nominal ambient conditions and the aux. contact is closed. All the control voltages at 1, 2, 5, 8, 11, 14 and 18 are ON. B1+ is then connected to the positive end of the bank, B1- is connected to B2+ via SSR2, B2- is connected to B3+ via SSR5, B3- is connected to B4+ via SSR8 and so on. B6- is connected to the negative end of the bank via SSR18. This completes the total battery bank connection with B1 in the first position from the positive end and B6 in the last position at the negative end.

After a period of usage cell B3 will have the lowest voltage. At that time it will be shifted to first position from the positive end. To achieve that the control switch needs to be moved to S3. At S3, control voltages at 2, 6, 7, 8, 11, 14 and 17 are ON. B3+ is connected to positive end via SSR7. B3- is connected to B4+ via SSR8. B4- is connected to B5+ via SSSR11 and so on. B6- is connected to B1+ via SSR17. B1- is connected to B2+ via SSR2 and B2- is connected to negative end via SSR6.

It was also determined that some features are needed in the control structure for safe operation of the circuit. First, shifting the control switch from S1 to S3 must be direct without going through any intermediate steps, e.g. S2. Secondly, SSRs that are turned ON with control switch at S1 must be given sufficient time to turn OFF completely before the switch is connected to S3. Hence a logic controller needs to be programmed for the control switch operation with all the necessary safety features and time delays to account for the Transient reverse recovery (Trr) time. Allen Bradley RSLogix 5000 is used to develop the control program for this purpose.

V. Testing of cell switching scheme

Operation of the SSRs was evaluated in a laboratory environment. The experimental configuration was made up of 24 ALA cells connected in series for a nominal 52 V battery voltage. The combined battery system has approximately 28 kWh of energy storage. The SSR device used in the test is GA8 6B02 from Crouzet [10]:

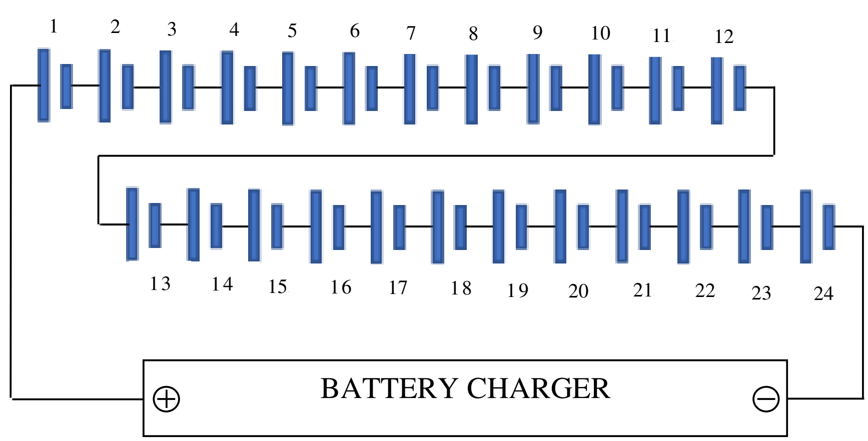

Fig. 6: Experimental battery bank series configuration.

The interconnection of the battery banks is shown in Fig. 6. to the battery system was charged from a Xantrex XW 6048 converter. Set 1 is connected to the positive end first and a complete charging cycle is done. Individual cell voltages are noted before reversing the order, i.e., set 2 is connected to the positive end and another charging cycle is completed.

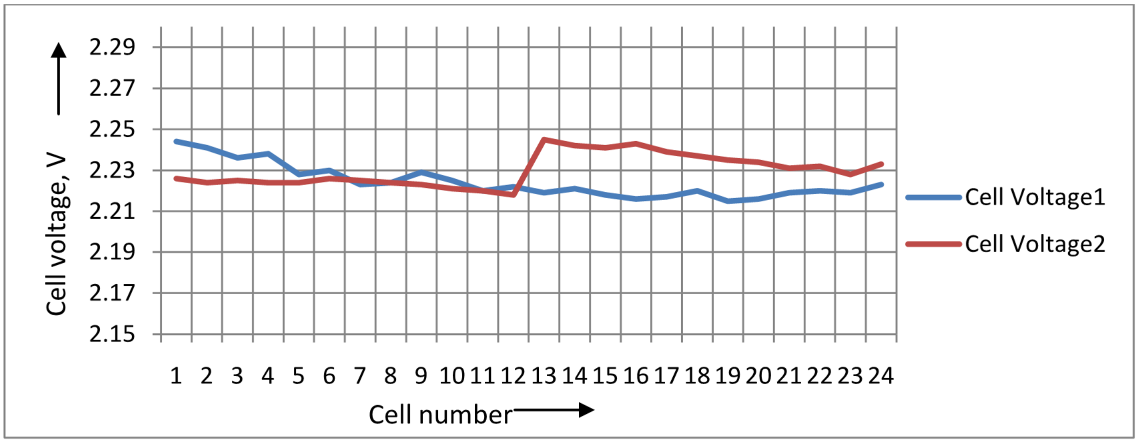

Fig. 7: Cell voltage reading after switching set positions.

After a complete charging cycle voltage of cell #1 is recorded at a high level of 2.244 volts in the plot for “Cell Voltage 1” above (Blue line). This cell voltage is reduced to 2.226 volts when set 2 is connected at the positive terminal (“Cell Voltage 2 – Red line”). Similarly, voltage of cell #13 is 2.219 volts in the first arrangement, but changes to 2.245 volts when set 2 is connected at the positive terminal. Using the same principle if the cell with lowest voltage is brought to 1st position at the positive terminal then its voltage will increase to become more level with the rest of the cells in the battery bank. Results show that difference in cell voltages of the battery bank in the laboratory reduced to a certain extent after switching and charging with different combinations.

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