Rotational Balancing for Parallel Connection of Batteries and Reducing the Number of Components in Multi-level Inverters

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Abstract

The paper aims to try to push the current concept about reduced switch count Multi-level inverter (RSC-MLI) for battery storage systems. They can be used to reduce the count of Mosfets used in Home storage systems (HSS); However, it would require precise Voltage measuring instruments and a complexer code to control the switching of Mosfets. To smooth the on/off step function, one can also use an inductor.

The research sparked interest during Covid phase when the prices of certain Mosfets increased 20 folds.
Rotational Balancing for Parallel Connection of Batteries and Reducing the Number of Components in Multi-level Inverters

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Abstract: Multi-level Inverters (MLIs) are in high demand due to the current energy crisis and their applications in different DC energy sources. MLIs offer high-quality output and better control over a DC source. However, they are facing a challenge with device count and size. Moreover, research on decommissioned batteries emphasises the value of lost energy in batteries. This paper presents the Switched Series-Parallel Sources Multi-level Inverter with rotational balancing as a better alternative to the Cascaded Half-Bridge Multi-level Inverter. Rotational balancing can balance cell voltage up to 1mV and utilises a cell’s total energy, unlike active or passive balancing. The paper shows the usage of rotational balancing for parallel connection of batteries to increase current output, closely manage voltages, and reduce the number of components. Switch voltage rating, possible circuit connections and challenges in actual implementation are also presented.

Keywords: multi-level inverter (MLI); switched series-parallel sources multi-level inverter (SSPS-MLI); batteries; battery balancing; rotational balancing

1. Introduction

Large battery storage systems support power grids [1–3], and smaller ones are used in electric cars [4]. Battery voltages of up to several hundred volts (230 V / 400 V) are required in battery storage systems. However, the cell voltage of a battery is only a few volts (e.g. 2.75 V - 3.6 V for the lithium-ion battery and 2 V - 3.2 V for Li-iron phosphate batteries), making it necessary to connect many individual battery cells in series to generate the required load voltage. At the same time, the current has to be discharged from the battery as per the requirement. In terms of C-rate, it can range anywhere from 0C to 6C. Another alternative to increasing C-rate is connecting batteries in parallel to increase the current.

DC-AC power conversion through a Multi-level Inverter (MLI) has become a key technology in generating, transmitting, distributing, and utilising electric energy [3,5,6]. In addition, the use of energy storage systems is also on the rise [7]. MLI experienced a boost in product development in the last decade due to decreasing semiconductor costs and technological improvements [8,9]. However, the price of semiconductors has increased recently due to international politics, the COVID-19 pandemic, and other supply chain limitations [10–12]. Therefore, it is imperative to find cost-effective ways to operate MLIs, given the rising costs of semiconductors.

Several methods have been developed to operate MLIs cost-effectively. One of the workarounds is by using three or four different battery cells in series as one battery module, providing a higher voltage in an MLI [9]. However, the method comes at the cost of losing control over individual battery cells and the remaining power capacity [9].

Another technology to reduce the costs and components without losing individual battery control is the Reduced Switch Count Multi-level Inverter (RSC-MLI) [13]. To work on RSC-MLI, we compared different RSC-MLI topologies to select the most suitable variant for this study. The Switched Series-Parallel Sources Multi-level Inverter (SSPS-MLI)
was the most suitable variant. Extended work on the SSPS-MLI can be found by Gowd et al. with solar modules as DC sources instead of batteries [14].

Given the benefits of SSPS-MLI, the study aimed to find the challenges involved in developing products of SSPS-MLI with batteries as an energy storage unit. The study analysed the switching states of the SSPS MLI topology with rotational balancing. The article is organised into several sections. Section 2 provides a description of SSPS-MLI and rotational balancing. Section 3 describes the methods used to find the challenges and the tested solutions. Section 4 depicts the results along with their assessment. Section 5 discusses the results, and presents the challenges. Finally, Section 6 gives the conclusion of this article along with proposals for future studies.

2. Description of technologies

2.1 SSPS MLI

SSPS-MLI, as shown in Figure 1, allows individual battery control with fewer MOSFETs than in Cascaded Half-Bridge (CHB) MLI. A detailed description of CHB has been provided earlier [15]. Furthermore, turning MOSFETs on or off allows complete control over the current path. Hence, the batteries can be connected individually either in series or in parallel. Higher-order SSPS MLI are shown in Appendices A2-A4. The switching states that can be realised from the circuit in Figure 1 are shown in Table 1.

![Figure 1. SSPS-MLI. ‘A’ represents Ammeter, ‘B’ represents Batteries, and switch ‘S’ represents a MOSFET, whereas both terminologies are used interchangeably.](image)

<table>
<thead>
<tr>
<th>Switching states</th>
<th>Switching states</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series connection of the two batteries B1 and B2</td>
<td>S2, S4 On and S1, S3, S5 Off</td>
</tr>
<tr>
<td>Parallel connection of the two batteries B1 and B2</td>
<td>S1, S3, S4 On and S2, S5 Off</td>
</tr>
<tr>
<td>Bridging the two batteries B1 and B2</td>
<td>S5 On and S1, S2, S3, S4 Off</td>
</tr>
<tr>
<td>Bypassing battery B1</td>
<td>S3, S4 On and S1, S2, S5 Off</td>
</tr>
<tr>
<td>Bypassing battery B2</td>
<td>S1, S4 On and S2, S3, S5 Off</td>
</tr>
</tbody>
</table>
Depending on the voltage and current requirements, the Battery Management System (BMS) can decide if the topology needs to connect the batteries in series or parallel (shown in Appendices A5-A14) to generate a higher voltage or a higher current, respectively. An example for the use of a BMS is in electric cars. An electric motor is used to generate torque in electric cars. When stationary, electric cars require a high torque to start moving and to overcome inertia. The high torque can be achieved by delivering a higher current, which in turn is achieved by discharging the battery with a higher discharge rate (2C, 3C, or more, depending upon the manufacturer) [16]. However, using high discharge rates in applications such as starting an electric car has the drawback of shortening the battery’s life span and increasing the power losses in the battery circuit (P=I²R).

However, in SSPS-MLI, the parallel mode can be used to deliver higher currents than CHB-MLI in storage applications. The requirement for the parallel connection of batteries is that the batteries must have the same voltage. For example, a 3.6 V battery should not be connected with a 3.0 V battery, and it is better to use the batteries with the same capacity, age, and manufacturer.

In contrast, when the car is moving at high speed, it does not require a high torque or high current. Thus, the SSPS-MLI circuit can be switched to a series connection, which delivers higher voltage and lowers current.

2.2 Balancing

In a battery pack, there are slight differences in the properties of each cell due to the manufacturing process. These differences include cell capacity, self-discharge rate, and temperature characteristics. Moreover, ageing effects in the battery further amplify these differences. The difference in capacity means that while charging the cells, some cells are not fully charged, while others are already fully charged (shown in Figure 2). Therefore, the charging process must be interrupted; otherwise, some individual cells will be overcharged, damaging the battery cells. The situation is similar during the discharging process; while some cells are fully discharged, others still have sufficient energy. Again, the discharge process must be stopped. Otherwise, the weaker cells will be over-discharged, damaging the battery cells.
Therefore, a BMS with charge balancing between the individual battery cells is necessary [17]. As the battery’s capacity is directly related to voltage, the balancing is done by monitoring the cell’s voltage and managing the battery voltage as close to one another as possible. For example, the Li-ion battery has a 100% state of charge (SoC) at 3.7 V and 0% SoC at 2.3 V. The most widespread methods are passive and active charge balancing. However, these methods costs energy and causes further losses [15].

2.3 Rotational Balancing

The method that will be used in this study is rotational balancing. In rotational balancing, while discharging, the highest capacity batteries are used the most and make the base of the sinusoid, and the lowest capacity batteries are used the least and make the peak of the sinusoid [15]. Figure 3 shows the output voltages that result from rotational balancing. In Figure 3, six cells with approximately 4 V are used to generate a sinusoidal wave. Battery 6 is at the base, representing that it was primarily used to discharge. It was selected by the master board for the longest time (as the base supply) because it was recognized as the one with the highest capacity compared to the other batteries.

Meanwhile, Battery 1 (bat1) was selected to engage for the shortest time (used at the peak) as it presented the least amount of capacity [15]. As the SoC and voltage are directly related, the battery’s capacity is estimated directly from the voltage. The MLI topology in the prototype is configurable and can be used to generate any required voltage. A 100-step MLI is shown in [15]. Similar connections of SSPS-MLI in series would allow us to generate higher voltage level sinusoidal waves such as 230 V or 400 V. The balancing continues until all the batteries reach the same capacity.
3. Materials and Method

The software used for the simulation was MatlabR2021 and PLECS 4.0.4. In addition, SSPS-MLI was simulated in PLECS to enhance current CHB-MLI products [8] for energy storage. The SSPS-MLI consisted of seven MOSFETs and two batteries, as shown in Figure 1. The equivalent circuit of the given model in PLECS can be seen in Appendix A1.

This model can be expanded to contain three or four batteries, as shown in Appendices A2 and A3. Theoretically, the SSPS-MLI is flexible and can hold any number of batteries, as shown in Appendix A4. However, MOSFET’s voltage and current limit the number of batteries in an SSPS-MLI. For example, the MOSFETs used are based on the characteristics of the “PSMN1R0-30YLC” component from NXP. This specific component has a cut-off voltage of 30 V and can accommodate up to four batteries in one SSPS-MLI while considering the existing standards (Appendix A3).

SSPS-MLI with two batteries was used, as shown in Figure 1. DC voltage sources with 3.6 V simulated the batteries (B1, B2). The load was 1 Ω, and the current was also set to be 3.6 A.

Since the SSPS-MLI generates a sinusoidal wave, the following connections were made in positive and negative directions: (i) Series “S” (ii) Parallel “P” (iii) Bypass “BP” (iv) B1 and (v) B2. The combination made ten states as shown in Table 2, and the corresponding circuit diagrams can be seen in Appendices A4 - A14.

Table 2. Switching pattern of SSPS-MLI.

<table>
<thead>
<tr>
<th>Connection type</th>
<th>Phase Voltage Level</th>
<th>Switches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Battery circuit</td>
<td>S1</td>
</tr>
<tr>
<td>Series</td>
<td>2 V (B1+B2)</td>
<td>0</td>
</tr>
<tr>
<td>Parallel</td>
<td>V (B1+B2)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>+V (B1)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>+V (B2)</td>
<td>0</td>
</tr>
<tr>
<td>One cell</td>
<td>+Bypass</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>-Bypass</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 3. Output voltage waveform from six cells, from [8].
A switching time of 1 microsecond was used for simulations, that is, for every microsecond, a command was sent to one MOSFET in an SSPS-MLI to change its state. This value was selected based on the number of slave devices, communication protocol limitations, and signal transmission speed of the Master microcontroller.

Different scenarios for testing were considered after establishing the hardware and switching methodologies. The criteria for developing a simulation test pattern were based on comprehensiveness, and the most challenging scenario was chosen for simulation. The test method was kept constant in all simulations and was done in different phases. In the first phase, all MOSFETs were turned off (switch state=0). Then, the MOSFETs were switched on in such a way that both batteries were bypassed, i.e. (none of them were connected in the circuit), and then both the batteries were connected in series, then in parallel. The circuit was then changed to connect only one cell (B1), and then again both batteries were bypassed. In short, “0-BP-S-P-B1-BP”.

The batteries were simulated with the method mentioned above and with a voltage difference of (a) 0 V, (b) 0.1 V, (c) 0.1 V with an inductor, and (d) 1 mV (the current sensors in MLI can measure the voltage with the precision of 1 mV).

During the switching, it was found that complications could occur in practical applications if the batteries were in parallel and had different voltages, as shown in Figure 4. A parallel connection would cause the battery with the higher voltage (B1) to discharge into the battery with lower voltage (B2) until both the batteries have equal voltages. Such current flow can cause heating, leaking, or bulging in the lower voltage battery, and over-heating in the higher voltage battery as it drains rapidly. From an energy perspective, it is a waste of energy to charge another battery that may be dead or have worse efficiency.

![Figure 4. Parallel Batteries connection.](image)

Table 3 shows the switching of MOSFETs one at a time in the simulation method described above. As for the colour codes in the table, green represents a stable switching state, yellow is used for transitional stages, and the colour red describes the problem phase because both batteries would be parallel to one another without any external load.
Table 3. Simulation steps.

<table>
<thead>
<tr>
<th>Steps</th>
<th>State</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0-BP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>BP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>BP-S1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>BP-S2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>S</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>S-P1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>S-P2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>S-P3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>S-P4</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>P</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>B1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>P-BP2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>P-BP3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>BP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

The outputs were measured through a Voltmeter and Ammeter, as shown in Appendix A1.

4. Results

The results of simulations are divided into four parts, with each part presenting the results of each simulated scenario.

4.1 Ideal state

In the ideal state, both batteries would have the same voltage, and there will be no current flow between them. Such a scenario is shown in Figure 5. At 5 µs, both batteries were in series and had an individual voltage of 3.6 V, a total output voltage of 7.17 V, and an output current of 7.17 A. At point 10 µs, both batteries were in parallel and supplied an output voltage of 3.59 V with a current supply of 1.79 A from each battery, making the total output current 3.59 A.
4.2. 0.1 V difference

A slight difference in the voltages can lead to a large current within the parallel loop of the batteries. This fact was proven by the second experiment using a 0.1 V difference, that is, the voltage of B1 and B2 were 3.6 V and 3.5 V respectively. The results are shown in Figure 6.
The series connection remained unchanged, whereas a large current flow was noticed one step before the parallel connection at 9 µs. Ammeter 1 (A1) showed a +50 A current flow, whereas Ammeter 2 (A2) showed a current of -50 A, indicating that the current moved in the positive direction of B1. At 10 µs, B1 delivered a current of 51.77 A, whereas B2 delivered -48.2299 A. The total output current was 3.541 A. After this, B2 was taken out of the parallel phase, hence B1 delivered a total current of 3.589 A.

4.3 Inductor

An inductor of 1 nH was added to the previous simulation, even though this simulation would increase the number of components. The addition of the inductor was simulated to reduce the current’s impact on the circuit by dampening the instantaneous increase in current observed in the previous simulation. The effect of the inductor is shown in Figure 7. The inductor turned the current’s step-form to a ramp form at point 9 µs. The peak current was 100 A at 10 µs. Even though the output current remained the same, a gradual increase in the output voltage occurred between points 9 µs. and 10 µs.
Figure 7. B1=3.6V. B2=3.5V with inductor.

4.4 Rotational balancing

Figure 8 shows the effect of rotational balancing on voltage in an MLI. The BMS automatically switched individual batteries for voltage balancing. In the same way, the BMS could be programmed to consider series or parallel connections depending on the load.
Charge balancing using rotational balancing was done on 100 batteries, shown in Figure 8. The 100 cells started balancing with the difference between the maximum and minimum voltages of 0.155 V. Initially, the batteries were charged with 2.5 A, and after 2250 s (37.5 min), all batteries were balanced with a voltage difference of 0.015 V. In the next phase, after 5625 s (93.75 min) the batteries were charged with 1 A, and the voltage difference between maximum and minimum voltages further reduced to 1 mV. This shows that batteries are ideally balanced and as long as the BMS of MLI is active, the battery voltages will be managed very closely.

Since rotational balancing balanced the voltages of the batteries up to 1 mV, the fourth experiment was done with rotational balancing in the SSPS-MLI circuit with a 1 mV difference. Thus, B1 was simulated with 3.600 V and B2 with 3.599 V. The results are shown in Figure 9.
Again, the series connection did not show any change, and the total output voltage remained the sum of both batteries. Whereas for the parallel battery scenario, at 9 µs, the current flow resumed. The observation from Ammeters 1 and 2 shows that B1 discharged 0.5 A into B2, representing a reduction of 100 folds compared to simulation in section 4.2. Therefore, it can be concluded that by managing the voltages closely, we can significantly reduce the current flow between the batteries. As per the potential difference at point 10 µs, B1 delivered +2.29 A and B2 delivered +1.29 A. The total output voltage and current were 3.59 V and 3.59 A, respectively.

5. Discussion

5.1 Ideal state

The figures in the results show the current flow in Ammeter 1 and Ammeter 2 of Appendix A1, as well as the output current and voltage. This template was used throughout the simulations to explain the current and voltage in SSPS-MLI circuits. It can be seen that from 1 µs to 5 µs, no current flowed in the circuit. At 5 µs, the batteries were in series and delivered a combined voltage of 7.17 V and an output current of 3.59 A. At 9 µs, the batteries were in parallel without an external circuit, and due to the equal voltage, no current flow occurred between the batteries. As we move to 10 µs, the circuit was connected with the load, and each battery gave an output voltage of 3.6 V, whereas the current flow of B1 and B2 is 1.79 A. Finally, at 11 µs, B1 alone supported the output load with 3.59 V and 3.59 A.
Finally, compared to the input voltage, the small voltage drop observed at the output is related to the actual values of the electronic components used, which caused a voltage drop due to internal resistance.

5.2 0.1. V difference

At 5 µs, both the batteries were in series and generated a combined output voltage of 7.1 V. At 9 µs, due to the voltage difference, B1 tried to balance the B2, and hence we can see 50 A current flowed from B1 to B2. The current flow was observed through Ammeters 1 and 2, each showing a different current direction. At 10 µs, the batteries were connected with the load and provided the output voltage of 3.54 V and an output current of 3.541 A. However, the internal voltage balancing continued within the parallel batteries and caused high currents. High currents over a long period can cause fire due to overheating batteries [18,19]. From the current flows in Ammeter 1 and Ammeter 2 of 51.77 A and -48.23 A, respectively, it can be concluded that the current flow from B1 and B2 was 1.77 A. A further voltage drop observed can be attributed to the internal balancing (current flow) between the batteries. At 11 µs, B1 supported the output load with 3.59 V and 3.59 A.

5.3 Inductor

As noted earlier, there was a change in the current profile from a step shape to a ramp shape after the introduction of a 1 nH inductor. The increase in current to 100 A from B1 during the ramp stage implied that the battery was in danger of being destroyed. Moreover, the inductor is an extra component, and thus adds another cost. For these reasons, the circuit design was discarded as a viable method to balance the voltages.

5.4 Rotational balancing

As previously mentioned, we can see the batteries getting balanced at 37.5 min. We can conclude that the quality of balancing (in millivolts) and the time required to balance all the cells are dependent on the charge rate. High current balances the batteries faster, and low currents ensure high-quality balancing. With such reasoning, it is better to have more batteries in parallel, which would slow ageing, generate less heat from battery power losses, and provide higher output current. This interpretation is also supported by research from Moo et al. [20]. Hence, if a higher discharge current is required for greater torque in the machine, SSPS-MLI would still be a better option than CHB-MLI (discharging one battery with a higher C-rate).

As balancing starts at different battery voltages, the following advantages of rotational balancing can be deduced: (a) The battery with different capacities, compositions, and manufacturers can be used together. (b) Every cell’s total capacity is utilised, thus delivering an average total capacity of all the cells in a battery without losses. (c) The output voltage is configurable. (d) Since each cell’s current and voltage are constantly measured, it can also estimate the battery’s SoC and bypass all the redundant cells after reaching the output voltage. Furthermore, since MLI offers modular construction, the user can define the number of redundant cells for each application. (e) Batteries with different “parameters” (manufacturer, efficiency, capacity, life state, and size) can be used without any need for sorting. [15].

Considering the simulation with a 1 mV difference in batteries, there was not much of a difference in series connection at 5 µs. However, at 9 µs, the batteries were in parallel, and through Ammeters 1 and 2, a current flow of 0.5 A was observed from B1 to B2. Such a current is within the safety limit of the circuit and can be tolerated by the system. At 10 µs, we observed from Ammeter 1 and Ammeter 2 that 2.29 A flowed from B1, and 1.29 A flowed from B2, respectively, that is, both batteries contributed to the load, and there was no current exchange between the batteries in the parallel phase. Therefore, B1 provided 64% current, B2 provided 36% current to the load, and the output voltage and current were 3.59 V and 3.59 A, respectively.
5.5 Practical Implication

It is clear from Sections 4.1 and 4.2 that voltage management of battery is important for a SSPS-MLI inverter. Based on the simulation in section 4.3, using an inductor does not provide the solution to prevent high currents. From Section 4.4, rotational balancing technology is used to show how the voltage can be managed to 1mV. This voltage difference is then used in Fig. 9 to simulate how the batteries would behave. This may seem like a good result in the beginning. However, experiments need to be done to confirm the simulations. Furthermore, for the circuit shown in Figure 1, even though the number of MOSFETs are reduced compared to traditional CHB-MLI, the number of gate drivers may need to be increased to control the MOSFET and a more complex controlling strategy would be required.

6. Conclusion

SSPS-MLI is a better option to reduce the number of MOSFETs in a circuit and use batteries in parallel connection to reduce the output current of the individual battery. Smaller current output means discharging the battery at a lower C-rate, thereby increasing the battery’s lifespan, and lowering the heat generated in the battery pack. Hence, SSPS-MLI with rotational balancing can provide an ideal balance between RSC-MLI and individual battery control for energy efficiency. The balancing quality depends on the discharge rate, and the quality is better at lower current discharge from batteries. Furthermore, increasing the number of parallel batteries in the circuit will decrease each battery’s discharge current. Lastly, we can significantly reduce the current flow between the batteries by managing the voltages closely. By using rotational balancing, we can ensure that batteries have the same capacity without any energy loss and that the batteries’ capacity is used to the full. However, this method also brings new challenges. Firstly, a complex controlling strategy is needed. Moreover, the number of gate drivers would increase.

Finally, most of the current market products use Li-ion batteries. They are easier to use but are prone to burning [19] than Li-iron phosphate batteries [21]. Future work will focus on making a BMS for Li-iron phosphate batteries that can accurately predict SoC as per the latest Chinese standards [22].

List of Abbreviations

Multi-level Inverter (MLI)
Switched Series-Parallel Sources Multi-level inverter (SSPS-MLI)
Reduced Switch Count Multi-level Inverter (RSC-MLI)
Cascaded Half-Bridge Multi-level Inverter (CHB-MLI)
Battery Management System (BMS)

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Conflicts of Interest: Declare conflicts of interest or state “The authors declare no conflict of interest.”

Appendix A.
Figure A1. PLECS model for SSPS-MLI for two batteries

Figure A2. SSPS-MLI for three batteries

Figure A3. SSPS-MLI for four batteries
Figure A4. SSPS-MLI for ‘n’ number of batteries

Figure A5. Switch states for positive current flow of batteries in series.

Figure A6. Switch states for positive current flow of batteries in parallel.
Figure A7. Switch state for positive current flow of battery 1 only

Figure A8. Switch state for positive current flow of battery 2 only
Figure A9. Switch state for bypassing the batteries

Figure A10. Switch state for bypassing the batteries
Figure A11. Switch states for negative current flow of battery 1 only.

Figure A12. Switch states for negative current flow of batteries in parallel.
Figure A13. Switch states for negative current flow of battery 2 only.

Figure A14. Switch states for negative current flow of batteries in series.

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