A Hybrid Cascaded Multilevel Converter for Battery Energy Management
Applied in Electric Vehicles

L. ANIL KUMAR¹, P. JAGADEESH²

¹PG Scholar, Dept of EEE, Samskruti College of Engineering & Technology, Hyderabad, TS, India.
²Assistant Professor, Dept of EEE, Samskruti College of Engineering & Technology, Hyderabad, TS, India.

Abstract: In electric vehicle (EV) energy storage systems, a large number of battery cells are usually connected in series to enhance the output voltage for motor driving. The difference in electrochemical characters will cause state-of-charge (SOC) and terminal voltage imbalance between different cells. In this paper, a hybrid cascaded multilevel converter which involves both battery energy management and motor drives is proposed for EV. In the proposed topology, each battery cell can be controlled to be connected into the circuit or to be bypassed by a half-bridge converter. All half bridges are cascaded to output a staircase shape dc voltage. Then, an H-bridge converter is used to change the direction of the dc bus voltages to make up ac voltages. The outputs of the converter are multilevel voltages with less harmonics and lower dv/dt, which is helpful to improve the performance of the motor drives. By separate control according to the SOC of each cell, the energy utilization ratio of the batteries can be improved. The imbalance of terminal voltage and SOC can also be avoided, fault-tolerant can be easily realized by modular cascaded circuit, so the life of the battery stack will be extended. Simulation and experiments are implemented to verify the performance of the proposed converter.

Keywords: Battery Cell, Charging And Discharging, Electric Vehicle (EV), Hybrid Cascaded Multilevel Converter, Voltage Balance.

I. INTRODUCTION

An energy storage system plays an important role in electric vehicles (EV). Batteries, such as lead-acid or lithium batteries, are the most popular units because of their appropriate energy density and cost. Since the voltages of these kinds of battery cells are relatively low, a large number of battery cells need to be connected in series to meet the voltage requirement of the motor drive [1], [2]. Because of the manufacturing variability, cell architecture and degradation with use, the characters such as volume and resistance will be different between these cascaded battery cells. In a traditional method, all the battery cells are directly connected in series and are charged or discharged by the same current, the terminal voltage and state-of-charge (SOC) will be different because of the electrochemical characteristic differences between the battery cells. The charge and discharge have to be stopped even though only one of the cells reaches its cut-off voltage. Moreover, when any cell is fatally damaged, the whole battery stack cannot be used anymore. So the battery cell screening must be processed to reduce these differences, and voltage or SOC equalization circuit is often needed in practical applications to protect the battery cells from overcharging or over discharging [3], [4]. Generally, there are two kinds of equalization circuits. The first one consumes the redundant energy on parallel resistance to keep the terminal voltage of all cells equal. For example, in charging course, if one cell arrives at its cut-off voltage, the available energy in other cells must be consumed in their parallel-connected resistances. So the energy utilization ratio is very low. Another kind of equalization circuit is composed of a group of inductances or transformers and converters, which can realize energy transfer between battery cells. The energy in the cells with higher terminal voltage or SOC can be transferred to others to realize the voltage and SOC equalization. Since the voltage balance is realized by energy exchange between cells, the energy utilization ratio is improved. The disadvantage is that a lot of inductances or isolated multi winding transformers are required in these topologies, and the control of the converters is also complex [5]–[13]. Some studies have been implemented to simplify the circuit and improve the balance speed by multistage equalization [9]–[13]. Some zero voltage and zero current switching techniques are also used to reduce the loss of the equalization circuit [13]. Multilevel converters are widely used in medium or high voltage motor drives [14]–[19]. If their flying capacitors or isolated dc sources are replaced by the battery cells, the battery cells can be cascaded in series combining with the converters instead of connection in series directly. In [20]–[24], the cascaded H-bridge converters are used for the voltage balance of the battery cells. Each H-bridge cell is used to control one battery cell; then the voltage balance can be realized by the separate control of charging and discharging. The output voltage of the converter is multilevel which is suitable for the motor drives. When used for power grid, the filter inductance can be greatly reduced.

The cascaded topology has better fault-tolerant ability by its modular design, and has no limitation on the number of cascaded cells, so it is very suitable to produce a higher
voltage output using these low-voltage battery cells, especially for the application in power grid. Similar to the voltage balance method in traditional multilevel converters, especially to the STATCOM using flying capacitors, the voltage balance control of the battery cells can also be realized by the adjustment of the modulation ratio of each H-bridge [25]. Compared to the traditional voltage balance circuit, the multilevel converters are very suitable for the balance of battery cells. Besides the cascaded H-bridge circuit, some other hybrid cascaded topologies are proposed in [18], [19] which use fewer devices to realize the same output. Because of the power density limitation of batteries, some ultracapacitors are used to improve the power density. Some converters must be used for the battery and ultracapacitor combination[26],[27].Multilevel converters with battery cells are also very convenient for the combination of battery and ultracapacitors. A hybrid cascaded multilevel converter is proposed in this paper which can realize the terminal voltage or SOC balance between the battery cells. The converter can also realize the charge and discharge control of the battery cells. A desired ac voltage can be output at the H-bridge sides to drive the electric motor, or to connect to the power grid. So additional battery chargers or motor drive inverters are not necessary any more under this situation. The ac output of the converter is multilevel voltage, while the number of voltage levels is proportional to the number of cascaded battery cells. So in the applications of EV or power grid with a larger number of battery cells, the output ac voltage is approximately ideal sine waves. The harmonics and dv/dt can be greatly reduced than the traditional two-level converters. The proposed converter with modular design can realize the fault redundancy and high reliability easily. Simulation and experimental results are proposed to verify the performance of the proposed hybrid cascaded multilevel converter in this paper.

II. TOPOLOGY OF THE HYBRID CASCADED MULTILEVEL CONVERTER

One of the popular voltage balance circuits by energy transfer is shown in Fig. 1 [5], [28]. There is a half-bridge arm and an inductance between every two nearby battery cells. So the number of switching devices in the balance circuit is 2n-2 and the number of inductance is n-1 where n is the number of the battery cells. In this circuit, an additional inverter is needed for the motor drive and a charger is usually needed for the battery recharge [29]. In fact, if the output of the inverter is connected with the three-phase ac source by some filter inductances, the battery recharge can also be realized by an additional control block which is similar with the PWM rectifier. The recharging current and voltage can be adjusted by the closed-loop voltage or power control of the rectifier. The hybrid-cascaded multilevel converter proposed in this paper is shown in Fig. 2, which includes two parts, the cascaded half-bridges with battery cells shown on the left and the H-bridge inverters shown on the right. The output of the cascaded half-bridges is the dc bus which is also connected to the dc input of the H-bridge. Each half-bridge can make the battery cell to be involved into the voltage producing or to be bypassed. Therefore, by control of the cascaded half-bridges, the number of battery cells connected in the circuit will be changed, that leads to a variable voltage to be produced at the dc bus. The H-bridge is just used to alternate the direction of the dc voltage to produce ac waveforms. Hence, the switching frequency of devices in the H-bridge equals to the base frequency of the desired ac voltage.

There are two kinds of power electronics devices in the proposed circuit. One is the low voltage devices used in the cascaded half-bridges which work in higher switching frequency to reduce harmonics, such as MOSFETs with low on-resistance. The other is the higher voltage devices used in the H-bridges which worked just in base frequency. So the high voltage large capacity devices such as GTO or IGCT can be used in the H-bridges. The three-phase converter topology is shown in Fig. 3. If the number of battery cells in each phase is n, then the

\[ P = S_x \cdot u_x \cdot i. \]  

(1)
devices used in one phase cascaded half-bridges is 2n. Compared to the traditional equalization circuit shown in Fig. 1, the number of devices is not increased significantly but the inductances are eliminated to enhanced the system power density and EMI issues.
A Hybrid Cascaded Multilevel Converter for Battery Energy Management Applied in Electric Vehicles

Since all the half-bridges can be controlled individually, a staircase shape half-sinusoidal-wave voltage can be produced on the dc bus and then a multilevel ac voltage can be formed at the output side of the H-bridge, the number of ac voltage levels is 2n+1 where n is the number of cascaded half-bridges in each phase. On the other hand, the more of the cascaded cells, the more voltage levels at the output side, and the output voltage is closer to the ideal sinusoidal. The dv/dt and the harmonics are very little. So it is a suitable topology for the energy storage system in electric vehicles and power grid.

III. CONTROL METHOD OF THE CONVERTER

For the cascade half-bridge converter, define the switching state as follows:

\[ S_x = \begin{cases} 
1 & \text{upper switch is conducted, lower switch is OFF} \\
0 & \text{lower switch is conducted, upper switch is OFF.} 
\end{cases} \]  \hspace{1cm} (1)

The modulation ratio \( m_x \) of each half bridge is defined as the average value of the switching state in a PWM period. In the relative half-bridge converter shown in Fig. 4, when \( S_x = 1 \), the battery is connected in the circuit and is discharged or charged which is determined by the direction of the external current. When \( S_x = 0 \), the battery cell is bypassed from the circuit, the battery is neither discharged nor charged. When \( 0 < m_x < 1 \), the half-bridge works in a switching state. The instantaneous discharging power from this cell is

\[ P = S_x \cdot u_x \cdot i. \]  \hspace{1cm} (1)

Here \( u_x \) is the battery cell voltage and \( i \) is the charging current on the dc bus. In the proposed converter, the H-bridge is just used to alternate the direction of the dc bus voltage, so the reference voltage of the dc bus is the absolute value of the ac reference voltage, just like a half-sinusoidal-wave at a steady state. It means that not all the battery cells are needed to supply the load at the same time. As the output current is the same for all cells connected in the circuit, the charged or discharged energy of each cell is determined by the period of this cell connected into the circuit, which can be used for the voltage or energy equalization. The cell with higher voltage or SOC can be discharged more or to be charged less in using, then the energy utilization ratio can be improved while the overcharge and over discharged can be avoided. For the cascaded multilevel converters, generally there are two kinds modulation method: phase-shift PWM and carrier- cascaded PWM. As the terminal voltage or SOC balance control must be realized by the PWM, so the carrier-cascaded PWM is suitable as the modulation ratio difference between different cells can be used for the balance control [30]–[32]. In the carrier-cascaded PWM, only one half-bridge converter in each phase is allowed to work in switching state, the others keep their state unchangeable with \( S_x = 1 \) or \( S_x = 0 \), so the switching loss can be reduced. When the converter is used to feed a load, or supply power to the power grid, the battery with higher terminal voltage or SOC is preferentially used to form the dc bus voltage with \( S_x = 1 \). The battery with lower terminal voltage or SOC will be controlled in switch state with \( 0 < m_x < 1 \) or be bypassed with \( S_x = 0 \).

The control of the converter and voltage equalization can be realized by a modified carrier-cascaded PWM method as shown in Fig. 4. The position of the battery cells in the carrier wave is determined by their terminal voltages. In the discharging process, the battery cells with higher voltage are placed at the bottom layer of the carrier wave while the cells with lower voltage at the top layer. Then, the cells at the top layer will be used less and less energy is consumed from these cells. In the proposed PWM method, the carrier arranged by terminal voltage can realize the terminal voltage balance, while the carrier arranged by SOC can realize the SOC balance. Since the SOC is difficult to be estimated in the batteries in practice, the terminal voltage balance is usually used. Normally, the cut-off voltage during charge and discharge will not change in spite of the variation of manufacturing variability, cell architecture, and degradation with use. So the overcharge and over discharge can also be eliminated even the terminal voltages are used instead of the SOC for the carrier-wave arrangement. To reduce the dv/dt and EMI, only one half-bridge is allowed to change its switching state at the same time for the continuous reference voltage. Therefore, the carrier wave is only rearranged when the modulation wave is zero and the rearranged carrier only becomes effective when the carrier wave is zero.

\[ u_{x1} > u_{x2} > u_{x3} \]

Fig. 5. Carrier wave during discharging.
So the carrier wave is only rearranged at most twice during one reference ac voltage cycle as shown in Fig. 5. The battery’s terminal voltage and SOC change very slowly during the normal use, so the carrier wave updated by base frequency is enough for the voltage and SOC balance. If the number of the cascaded cells is large enough, all the half-bridges can just work in switch-on or switch-off state to form the staircase shape voltage. So the switching frequency of all the half-bridges can only be base frequency as shown in Fig. 6, where the output ac voltage is still very approach to the ideal sinusoidal wave which is similar with the multilevel converter in [32].

![Fig. 6. Base frequency modulation.](image)

When one cell is damaged, the half-bridge can be bypassed, and there is no influence on the other cells. The output voltage of the phase with bypassed cell will be reduced. For symmetry, the three-phase reference voltage must be reduced to fit the output voltage ability. To improve the output voltage, the neutral shift three-phase PWM can be adopted. The bypass method and the neutral shift PWM is very similar with the method explained in [20], [21].

### IV. LOSS ANALYSIS AND COMPARISON

Compared to the traditional circuit in Fig. 1, the circuit topology and voltage balance process is quite different. In the traditional circuit in Fig. 1, the three-phase two-level inverter is used for the discharging control and the energy transfer circuit is used for the voltage balance. In the proposed hybrid-cascaded circuit, the cascaded half-bridges are used for voltage balance control and also the discharging control associated with the H-bridge converters. The switching loss and the conduction losses in these two circuits are quite different. To do a clear comparison, the switching and conduction loss is analyzed in this section. In the hybrid-cascaded converter, the energy loss is composed of several parts

\[ J_{\text{Loss}} = J_{\text{I-B}} + J_{\text{I-H}} + J_{\text{c-B}} + J_{\text{c-H}}. \]  

(2)

Here, \( J_{\text{I}} \), \( J_{\text{H}} \) and \( J_{\text{c}} \) are the switching losses of the cascaded half-bridges and the H-bridge converters, while \( J_{\text{I}} \), \( J_{\text{H}} \) and \( J_{\text{c}} \) are the conduction losses. In the traditional circuit as shown in Fig. 1, the energy loss is composed by

\[ J_{\text{Loss}} = J_{\text{I-B}} + J_{\text{I-H}} + J_{\text{c-B}} + J_{\text{c-H}}. \]

(3)

where \( J_{\text{I}} \) and \( J_{\text{c}} \) are the switching losses of the three-phase inverter and the energy transfer circuit for voltage balance, \( J_{\text{H}} \) and \( J_{\text{c}} \) are the conduction losses. In the traditional circuit, the energy transfer circuit only works when there is some imbalance and only the parts between the unbalance cells need to work. So the switching and conduction losses will be very small if the battery cells are symmetrical.

![Fig.7. DC bus voltage output by the cascaded half-bridges.](image)

First, the switching loss is analyzed and compared under the requirement of same switching times in the output ac voltage. That means the equivalent switching frequency of the cascaded half-bridges in hybrid-cascaded inverter is the same as the traditional inverter. The switching loss is determined by the voltage and current stress on the semiconductor devices, and also the switching time

\[ J_{\text{s-H}} = \int_{0}^{T_{\text{switch}}} v_{i} i_{d} dt. \]  

(4)

In the proposed hybrid-cascaded converter, the H-bridge converter is only used to alternate the direction of the output voltage to produce the desired ac voltage as shown in Fig. 7, the devices in the H-bridge converter always switch when the dc bus voltage is zero. So the switching loss of the H-bridge is almost zero

\[ J_{\text{s-H}} \approx 0. \]  

(5)

The equivalent switching frequency of the half-bridges is the same as the traditional converter, but only one half-bridge is active at the any instantaneous in each phase. The voltage step of each half-bridge is much lower than the whole dc bus voltage in Fig. 7. So in a single switching course, the switching loss is only approximate \( 1/n \) of the one in traditional converter if the same device is adopted in both converters. Furthermore, if the lower conduction voltage drop and faster turn-off device such as MOSFET is used in the proposed converter, the switching loss of the half-bridge will be much smaller

\[ J_{\text{s-B}} < J_{\text{s-L}} / n. \]  

(6)

In the traditional circuit, the voltage balance circuit will still cause some switching loss determined by the voltage imbalance. So in the proposed new topology, the switching loss is much smaller compared to the traditional two-level inverter.
TABLE I: Comparison of The Switching and Conduction Loss of The Proposed Circuit And The Traditional One

<table>
<thead>
<tr>
<th>Circuit Type</th>
<th>Energy Transfer</th>
<th>Switching Loss</th>
<th>Conduction Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional circuit</td>
<td>Energy transfer circuit</td>
<td>determined by imbalance</td>
<td>determined by imbalance</td>
</tr>
<tr>
<td>3-phase inverter legs</td>
<td>$J_I$</td>
<td>$P_{s,j}$</td>
<td>$P_{c,j}$ = $I^2R_{c,j}$</td>
</tr>
<tr>
<td>Proposed novel circuit</td>
<td>Cascaded half-bridges</td>
<td>Much less than $J_{c,j}$</td>
<td>$P_{s,j}$ = $I^2R_{s,j}$</td>
</tr>
<tr>
<td>H-bridges</td>
<td>Near zero</td>
<td>$P_{c,j}$ = $I^2R_{c,j}$</td>
<td></td>
</tr>
</tbody>
</table>

The conduction loss is determined by the on-resistance of the switching devices and the current value. Whatever the switching state, one switch device in each half-bridge and two devices in H-bridge are connected in the circuit of each phase, so the conduction loss power can be calculated by

$$P_{c,j} = I^2R_{c,j} \cdot n$$

(7)

$$P_{c,H} = I^2R_{c,H} \cdot 2.$$  (8)

Here, $I$ is the rms value of the output current, $R_{c,B}$ is the on-resistance of the MOSFET in the half-bridge, $R_{c,H}$ is the device on-resistance used in the H-bridge, and $n$ is the number of the cascaded cells.

In the traditional three-phase inverter, only one device is connected in the circuit of each phase, the conduction loss power in each phase is just

$$P_{c,j} = I^2R_{c,j}.$$  (9)

where $R_{c,I}$ is the on-resistance of the devices used in the inverter. Normally, the same semiconductor devices can be used in the H-bridges and the traditional three-phase inverters, so the on-resistance of the inverters is almost the same as the H-bridges.

The on-loss of the H-bridges cannot be reduced, while the on-loss on cascaded half-bridges can be reduced furthermore by reducing the number of the cascaded cells. In practical applications, the battery module of 12 and 24 V can be used for the cascaded cells instead of the basic battery cell with only 2–3 V. Also the semiconductor devices with low on-resistance are used in the half-bridges. From the above analysis, the switching loss of the proposed converter is much less than the traditional converter, although the on-loss is larger than the traditional converter. The compared results are shown in Table I.

V. CHARGING METHOD

In the system using the proposed circuit in this paper, a dc voltage source is needed for the battery charging. The charging current and voltage can be controlled by the proposed converter itself according to the necessity of the battery cells. The charging circuit is shown in Fig. 8. A circuit breaker is used to switch the dc bus from the H-bridge to the dc voltage source. Furthermore, a filter inductor is connected in series with the dc source to realize the current control. The dc voltage can also be realized by the H-bridge and a capacitor as shown in Fig. 9. The H-bridge worked as a rectifier by the diodes and a steady dc voltage is with the help of the capacitors.

In the charging course of the battery, the charging current should be controlled. The current state equation is as follows:

$$R_{f,j} + L_{f} \frac{di}{dt} = u_{dc} - u_{charge}.$$  (10)

Here, $u_{dc}$ is the dc bus voltage output by the cascaded half bridges, $u_{charge}$ is the voltage of the dc source, and $R_f, L_f$ are the resistance and inductance of the inductive filter between the cascaded half-bridges and the dc source. By this charging method, the voltage of the dc source must be smaller than the possible maximum value of the dc bus

$$u_{charge} \leq u_{dc} \leq n \cdot u_0.$$  (11)

Fig. 8. Charging circuit of battery with dc source.

Fig. 9. Charging circuit of battery with ac source.

Fig. 10. Current control scheme for the battery charging.

Fig. 11. Carrier waves during charging.
Here, \( n \) is the number of the cascade half-bridges in each phase and \( u_0 \) is the discharging cut-off voltage of the battery cell. During the charging cycle, the voltages of the battery cells and the dc voltage source might be variable, so the switching states of the cascaded half-bridges will be switched to make the charging current constant. The charging current control scheme is shown in Fig. 10. A PI regulator is used to make the current constant by changing the output dc voltages of the cascaded cells. The voltage of the dc source is used as a feed-forward compensation at the output of the PI controller. In practical applications, the value of the dc source’s voltage is almost constant, so the feed forward compensation can also be removed and the variation of the dc source voltage can be compensated by the feedback of the PI controller. In charging state, the arrangement of the carrier waves will be opposite with discharge state. The battery cell with lower voltage will be placed in the bottom then these cells will absorb more energy from the dc source. The cells with higher voltages will be arranged at the top levels to make these cells absorb less energy. By the similar analysis as the discharging state, the positions of the carrier waves in charge state are shown in Fig. 9. During the regeneration mode of the motor drive, for example, when the EV is braking, the battery cells are also charged, so the modulation will also be changed to the charging mode as shown in Fig. 11. The energy charged into the battery cell is the same as (1)

\[
P_{\text{charge}} = u_o \cdot i = S_x \cdot u_o \cdot i
\]  

(12)

where \( S_x \) is the switching state of the bridge arms and \( i \) is the charging current controlled by the scheme shown in Fig. 9. When the reference dc bus voltage is variable, such as the half-sinusoidal-wave, all the battery cells will be charged intermittently because of the PWM as shown in Fig. 12. That is similar to the fast-charge method of the battery to improve the charging speed [33]. So the charging current in the proposed converter can be larger than the ordinary charging method. When the battery stack is charged by a steady dc source, the reference dc bus voltage is nearly constant. To realize the fast-charge of the battery cell, the carrier-wave must be forced to exchange the position which is not arranged by the SOC or terminal voltages any more. Then, the switching state of the half-bridges will be changed to produce intermittently charging current.

VI. EXPERIMENTAL RESULTS

To verify the performance of the proposed topology and the control method, a three-phase four-cell cascaded circuit is erected at lab. The platform is shown in Fig. 13. The lead-acid battery modules of 5 Ah and 12 V are used. The battery modules are monitored by the LEM Sentinel which can measure the voltage, temperature, and resistance of the battery modules. The measured information is transferred to the DSP controller by RS-232 communication. The voltages and currents are measured and recorded by YOKOGAWA ScopeCorder DL750. Since the SOC of the battery cells are difficult to be estimated, the terminal voltages are used for the PWM carrier-wave arrangement.

Fig. 12. Intermittent charging current of battery cells.

Fig. 13. Platform of the experiment.

Fig. 14. Triphase output voltage of multilevel.

\[
P = P^2 \cdot R \cdot \eta = 0.3 W.
\]  

(12)

Then, the efficiency drop caused by the conduction loss of the MOSFET in the whole phase is

\[
\Delta \eta = \frac{P \cdot R \cdot \eta}{U \cdot I \cdot \eta} = 1.75%.
\]  

(13)
So the conduction loss added by the equalization circuit is very small compared to the output power of the whole converter. Another device of MOSFET IPB22N03S4L-15 (Infineon) of 30 V, 22 A, and 14.6 mΩ will be used in our platform. The efficiency drop caused by the conduction loss $\Delta \eta = 1.38\%$ when the output current is 11 A. The three-phase output voltage is shown in Fig. 14. There are nine levels at each phase. So it approaches more to the ideal sinusoidal wave than the traditional two-level inverters. In a steady state, the FFT analysis result of the output ac phase voltage is shown in Fig. 15. It shows that the harmonics is little compared to the base-frequency component. An induction motor (IM) was driven with the variable voltage–variable-frequency (VVVF) control method. The parameters of the motor are shown in Table II. The dc bus voltage, ac output voltage, output current, and dc bus current are shown in Figs. 16 and 17, which indicate the whole process from start-up to the stable state of the relative IM. From Fig. 16, it is obvious that the output voltage levels keep increasing according to the acceleration of the motor speed. The stator current of the motor shown in Fig. 17 are of improved sinusoidal shape which can reflect the control performance of the motor. The dc bus current is also shown in Fig. 17. As the lag between the voltage and current phase, when the phase voltage change direction, the H-bridge will change its switching state too. But the phase ac current will change its direction after a period of time, so the direction of the dc bus current is reversed when the directions of phase voltage and current are different. The reversed dc bus current also reflects the reactive power of the load. As the induction motor is of nearly no load, the phase current is nearly $\pi/2$ lag with the phase voltage and the average dc current is almost zero in steady state. But in starting course,

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>0.55kW</td>
</tr>
<tr>
<td>Rated line voltage</td>
<td>380V</td>
</tr>
<tr>
<td>Rated line current</td>
<td>1.5A</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>2</td>
</tr>
<tr>
<td>Rated speed</td>
<td>1390rpm</td>
</tr>
</tbody>
</table>
the average dc bus voltage is positive which stands for the active power flow from the battery to the electric motor. When there is some load on the motor, the dc bus current is shown in Fig. 18. The reversed current is greatly reduced which means the average power is flowed from the converter to the motor.

Fig. 19. DC bus voltage and current when connecting with the DC source.

When the charging method introduced in above section is used with a steady dc source, the cascaded half-bridges are connected with the dc source first, then a charging current reference is given, the output dc bus voltage and the dc current of the whole course are recorded as a single figure by the YOKOGAWA Scope Corder. The two dynamic courses are zoomed and shown separately in Figs. 19 and 20. The dc bus voltage and the charging current when connecting with the dc source are shown in Fig. 19. It shows that when the dc source was connected, the cascaded half-bridges changed their switching state quickly to keep the charging current same as the reference value. In Fig. 18, there are two half-bridges working with \( S_x = 1 \) and the third working in switching state.

Fig. 20. DC bus voltage and charging current when a charging current reference was given.

When the charging current reference is given, the dc bus voltage will reduce first to establish the charging current as shown in Fig. 20. As the resistance in the filter inductance is very little, the voltage drop on the filtered inductance by dc current is also near zero, the dc bus voltage will become almost the same as the noncharging state. During the battery charging, if the voltage of the dc source is changed, the charging current control result is shown in Fig. 21. It can be seen even there are changes on dc source voltages, the charging current can be controlled well by the close-loop control of the dc current. As feed-forward compensation by the dc source voltage is not used in our system, there are some ripples in the dc current during dynamic course. From Figs. 19 and 21, it is clear that the proposed topology can be charged under external input dc voltages and the feasibility of the proposed charging method for practical EV application is proved. When the initial values of the terminal voltages are different, the voltage can be balanced during discharging with the proposed PWM. The curve of the three cells terminal voltages is shown in Fig. 22. The cell voltages are measured in every 10 min. We can find that the three terminal voltages will finally become equal voltage levels under the proposed voltage balance algorithm. It must be mentioned that the balanced terminal voltages are the operating voltages of the battery cells. The open-circuit voltage which can reflect the SOC cannot be balanced in real time. Due to the cell difference, the balanced terminal voltage will become different when the battery cells are out of use for a period of time.

Fig. 21. DC bus voltage and charging current during dc source voltage change.

Fig. 22. Terminal voltage balance result during discharging.
A Hybrid Cascaded Multilevel Converter for Battery Energy Management Applied in Electric Vehicles

VII. CONCLUSION

The hybrid-cascaded multilevel converter proposed in this paper can actualize the charging and discharging of the battery cells while the terminal voltage or SOC balance control can be realized at the same time. The proposed converter with modular structure can reach any number of cascaded levels and is suitable for the energy storage system control with low-voltage battery cells or battery modules. The fault module can be bypassed without affecting the running of the other ones, so the converter has a good fault-tolerant character which can significantly improve the system reliability. The PWM method with low switching loss for both discharging and charging control is proposed considering the balance control at the same time. The output of the circuit is multilevel ac voltages where the number of levels is proportional to the number of battery cells. So the output ac voltage is nearly the ideal sinusoidal wave which can improve the control performance of the motor control in EVs. A dc bus current control method for battery charging with external dc or ac source is also studied where the constant-current control can be realized and the additional charger is not needed any more. Experiments are implemented and the proposed circuit and control method are verified.

VIII. REFERENCES


