# HIGH PERFORMANCE HYBRID CASCADED MULTILEVEL INVERTER FOR BATTERY ENERGY MANAGEMENT APPLIED IN ELECTRIC VEHICLES

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**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, high performance hybrid cascaded multilevel inverter is proposed. It is based on two inds of power devices - MOSFET and IGBT. The cascaded inverter consists of three H-bridges. The DC voltage of each H-bridge meets the proportional relationship of 1:2:4 and the three modules are connected in series at the AC side. The low voltage bridge is composed of MOSFETs, while the medium and high voltage bridges are composed of IGBTs. This hybrid cascaded inverter can output at most 15 voltage levels at the AC side with rather low switching frequency. At the same time, it can fully exhibit the advantages of different power devices and make the inverter operation flexible. Voltage gradational method is adopted in the paper. It is shown that the conversion efficiency is increased, THD is reduced. Meanwhile, with different combination of switching states, the distribution of input active power in each H-bridge can be adjusted.**

**Index Terms –Battery cell, electric vehicles (EV), high performance hybrid cascaded multilevel inverter, 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 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 multiwinding 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 inmedium 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 Hbridge 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 high performance hybrid cascaded multilevel converter is proposed in this paper. 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 high performance hybrid cascaded multilevel converter in this paper.

## II. TOPOLOGY OF THE HIGH PERFORMANCE HYBRID CASCADED MULTILEVEL INVERTER

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 $2*n-2$ 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 Hbridge 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.

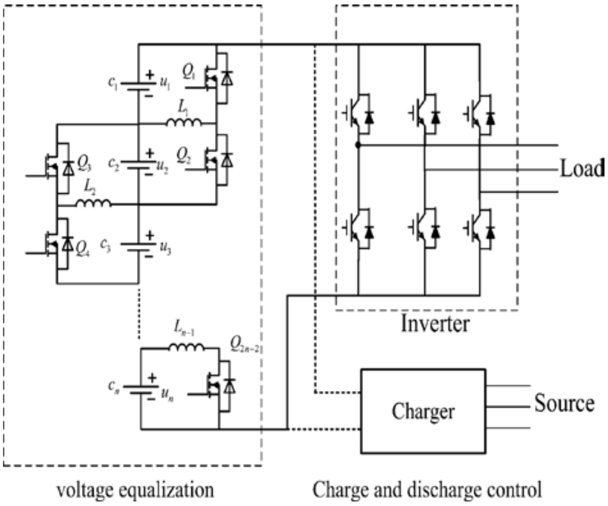

Fig. 1. Traditional power storage system with voltage equalization circuit and inverter.

There are two kinds of power electronics devices in the proposed circuit. One is the lowvoltage 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 devices used in one phase cascaded half-bridges is $2*n$. 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.

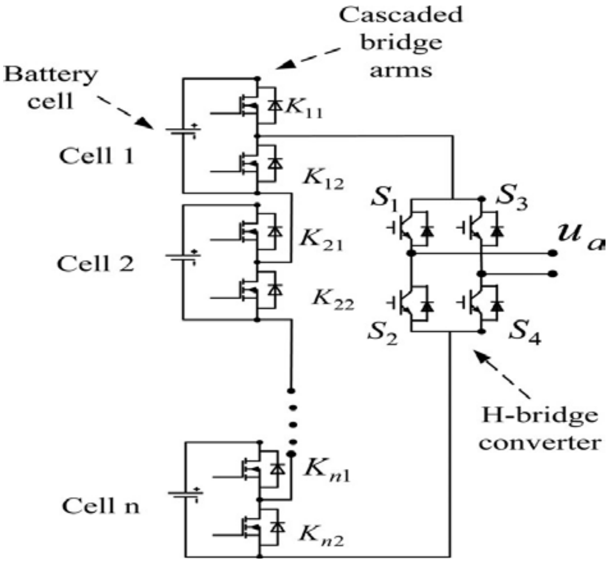

Fig. 2. Hybrid cascaded multilevel converter.

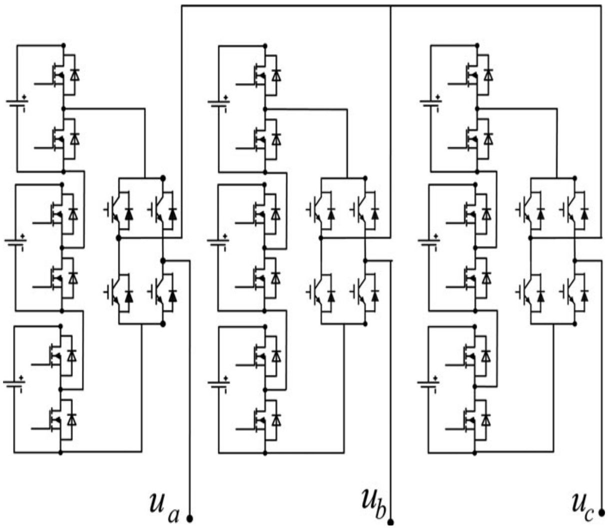

Fig. 3. Three-phase hybrid cascaded multilevel converter.

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 $2*n–1$ 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

In the paper, voltage gradational method is employed. In voltage gradational method, $V$ is supposed to be the required voltage at the AC side. It is the superposition result of $V0$, $2V0$ and $4V0$, as shown in (1). Here, coefficients $x$, $y$ and $z$ equal to 1, -1 or 0. '1', '-1' and '0' mean the H-bridge outputs positive, negative and zero DC bus voltage, respectively. It can be analyzed that to each needed voltage at the AC side, several superposition ways can be reached sometimes. For example, $V0$ has three superposition methods. They can be shown as '$V$=1·$V0$+0·2$V0$+0·4$V0$', '$V$=(1)·$V0$+1·2$V0$+0·4$V0$' and '$V$=(-1)·$V0$+(-1)·2$V0$+1·4$V0$'. In this way, some redundant states can be reached. The operation of HCI is more flexible (it will be shown in detail in the following part).

$$V \square\square x V0 \qquad y \square 2V0 \qquad z \square 4V0 \qquad (1)$$

The realization process of voltage gradational modulation method can be shown as follow. Firstly, according to the actual required amplitude and frequency, confirm the ideal instantaneous voltage value. Secondly, divide the ideal instantaneous voltage by the reference voltage $V0$. Round the result and get the voltage level to the instantaneous voltage.

## 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 Finally, confirm the concrete output voltage of each

$$J\text{Loss} = Js\ B + Js\ H + Jc\ B + Jc\ H\ . \quad (2)$$

Here, $Js\ B$ and $Js\ H$ are the switching losses of the cascaded half-bridges and the H-bridge converters, while $Jc\ H$ and $Jc\ B$ are the conduction losses.In the traditional circuit as shown in Fig. 1, the energy loss is composed by

$$J\text{Loss} = Js\ I + Js\ T + Jc\ I + Jc\ T \quad (3)$$

where $Js\ I$ and $Js\ T$ are the switching losses of the three-phase inverter and the energy transfer circuit for voltage balance. $Jc\ I$ and $Jc\ T$ are the conduction losses. In the traditional circuit, the energy transfer circuit onlyworks 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.

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 converter 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

$$Js = \int_0^{T_{sw\ it\ ch}} u \cdot idt.$$

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. 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

$$Js\ H \approx 0. \quad (5)$$

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 only the battery cell voltage which is much lower than the whole dc bus voltage in Fig. 1. 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

$$Js\ B < Js\ I\ /n. \quad (6)$$

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. 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

$$P_{cB} = I^2 R_{cB} \cdot n \quad (7)$$

$$P_{cH} = I^2 R_{cH} \cdot 2. \quad (8)$$

Here, $I$ is the rms value of the output current, $R_{cB}$ is the
on-resistance of the MOSFET in the half-bridge, $R_{cH}$ 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

$$P_{cI} = I^2 R_{cI} \quad (9)$$

where $R_{cI}$ 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 Hbridges. 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.

## V. EXPERIMENTAL RESULTS

Hear we verify the feasibility of the high performance hybrid cascaded structure with voltage gradational using MATLAB is implemented. In the model, one H-bridge is adopted. The structure is as same as mentioned above. The output frequency is 50Hz. The AC output waveforms with the modulation method used is
shown in Fig. 4 and 5.

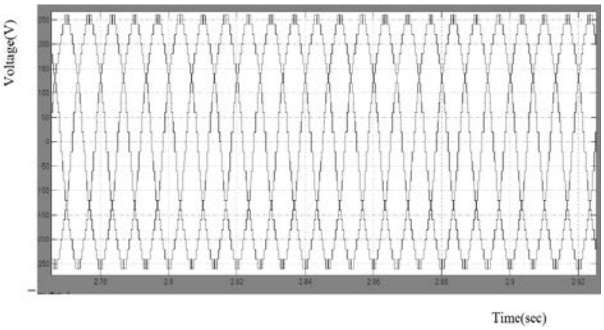

Fig 4 Three phase voltage output from high performance HCI

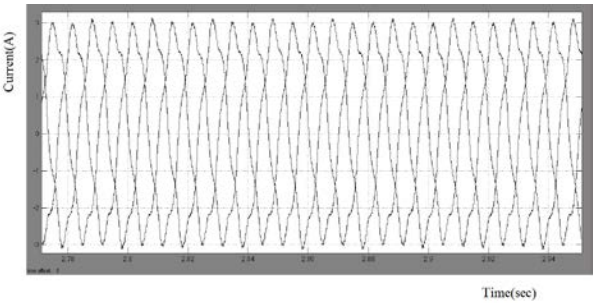

Fig 5 Three phase current output from high performance HCI

FFT analysis shows that total harmonic distortion is very less, compared to PWM modulation method. Out put waveforms of motor speed and torque is also shown in fig. 6.

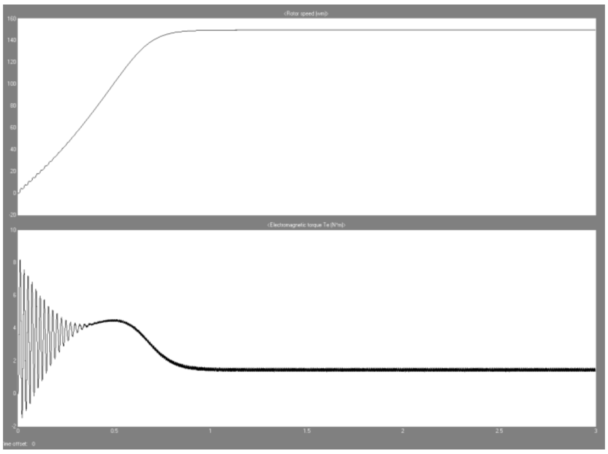

Fig 6 Motor speed and torque

## VI. CONCLUSIONS

In order to improve the performance of the renewable energy system, HCI is employed. In this paper, the topology and modulation method of a single-phase HCI are discussed.

Concretely, hybrid power devices are involved. In $V0$ Hbridge, power MOSFET is adopted while in $2V0$ and $4V0$ Hbridges, IGBT is employed. The advantage of each kind of device can be shown. The HCI is composed of one Hbridge.The DC voltage of H-bridge meets the proportional relationship of 1:2:4 and their AC sides are connected in series. As a result, it can output more voltage levels at the AC side with lower switching frequency. At the same time, voltage gradational method is adopted and discussed in detail in the paper. Based on the simulation results and experimental results, it can be concluded that high conversion efficiency and good output performance of HCI are reached. 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.

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