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FULLY AUTOMATED SOLAR GRASS CUTTER WITH REMOTE CONTROL AND MANUALLY OPERATED

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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 inelectrochemical 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 bypassedby 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

Keywords: solar grass cutter, remote control, SOC, motor drives.

1. INTRODUCTION

In electrical vehicles, energy storage system plays a crucial role. Lead –acid batteries or lithium batteries are most popular one because of their suitable energy density and cost. Due to low voltage of these kind of batteries need to be connected in series to get appropriate voltage requirement for driving motor. The volume and resistance of thee cascaded cells is different because of their variability in manufacturing,cell architecture and their usage. In the early electrical vehicles, the battery cells are usually connected in series and discharged or charged through the terminal voltage, same current and state-of-charge of each cell will be different because of difference in electro chemical characteristics of battery cells. If one cell reaches to desired cut-off voltage the charging and discharging of the battery cells will be stopped. In addition, in series connection if a cell gets damaged, we cannot use the whole battery stack. In order to avoid this battery screening must be employed and state of charge (SOC) or voltage equalization circuit is often needed for practical application in order to protect the battery cells from over discharging or charging. Normally, there are two kinds of equalization circuits are used. First one which consumes the unused energy on parallel resistance, to keep the voltage of all cells equal. For example, while charging phase, one cell attains the cut-off voltage, the available energy in other cells, consumed by parallel connected resistance. So, it will keep the energy utilization ratio verylow. Second kind of equalization circuit, it composed of a group of transformers or inductances and converters, which can realize transfer of energy between cells. The energy in cells with more terminal voltage or state of charge can transferred to other cells to realize state of charge and voltage equalization. By this, voltage balance is realized through energy exchange between cells, and this will improve the energy utilization ratio. The demerit is that it requires lot of inductances and isolated multiple winding transformers in this topology and it leads to complexity in operation of converter. So, some studies have been performed to simplify the circuit and also to improve balance speed by multiphase equalization. Such as zero current and zero voltage switching also performed to reduce the loss of equalization circuit.

Now-a-days multi converters are mostly used in the medium voltage and high voltage motor drives. If their isolated direct current sources or flying capacitors are replaced by battery cells and these battery cells are cascaded in series combining with converters instead of connecting directly in series. These H-bridges cascaded converters are used for balancing the voltage in the battery cells. Each H-bridge will control the one battery cell, and the voltage balance can be realized by separate control of discharging and charging. So, the output voltage ofthe converter is multilevel and it is suitable for motor drives. If we use this for power grid, their filter inductance can be reduced. The merits of cascaded topology is that, it has better fault tolerant capability by its design and there is no limitation on number of cells to be connected in cascaded i.e., we can connect 'n' number of cells in cascaded connection. So, it is the best method for producing high output voltage with low voltage battery cells, particularly in case of power grid, application. In the traditional method, particularly STATCOM voltage balance control can be realized by adjustment of modulation ratio of H-bridge. Compared to it, modern multilevel converters are best suitable for voltage balance in the battery cells. Part from cascaded H-bridge circuit, other cascaded models proposed with fewer devices to get the same output. Dueto voltage, power limitation of batteries, such as ultra-capacitors used to improve the power density. So, same converters must require the combination of ultra-capacitors and batter cells. So, multilevel converters with battery cells is very prominent for his kind of combination i.e., with ultra-capacitors and battery cells.The proposed Hybrid cascaded multilevel converter in this paper, it can realize the state of charge or terminal voltage between the cells. The proposed converter can realize the discharging control and charging control of the battery cells. And we get the desired alternating current voltage at the output of H-bridge converter sides and it can be used to drive the motor or connect to power grid. So, it does not require additional battery chargers or inverters in any circumstances. The obtained ac output voltage of the converter is multilevel voltage and the number of voltage levels is directly proportional to number of battery cells connected in cascaded. For the application of power grid, electrical vehicles a large number of battery cells needed and the alternating output voltage obtained is approximately equal to ideal sinusoidal waveform. The dv/dt and harmonics in the output alternating voltage are reduced greatly then the two-level converters. The advantage of proposed topology is that it can realize the fault reduction and also it has high reliability. Finally, experimental results and simulation results are performedin order to verify the performance of proposed cascaded multilevel converter.

2. CONVERTER TOPLOGY

2.1. TRADITIONAL 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 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 whichis 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.

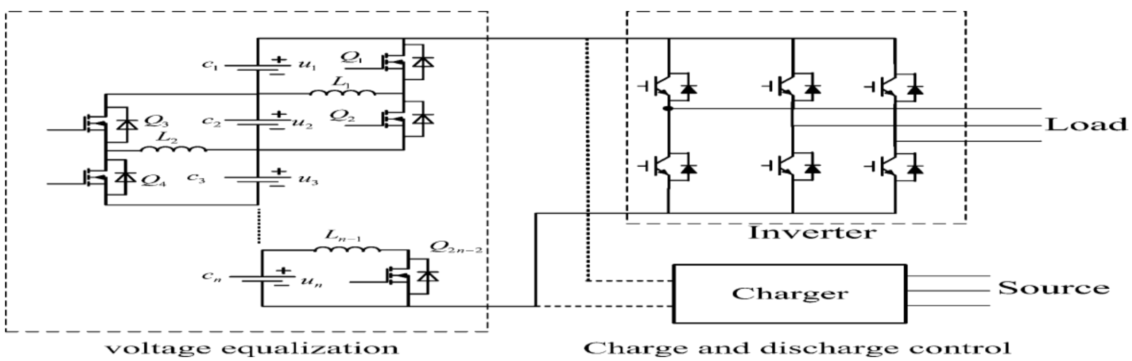

Figure 1. Traditional power storage system with voltage equalization circuit and inverter.

2.2 PROPOSED CONVERTER

There are two kinds of power electronics devices in the pro-posed circuit. One is the low voltage devices used in the cascaded half-bridges which work in higher switching frequency to re-duce 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.

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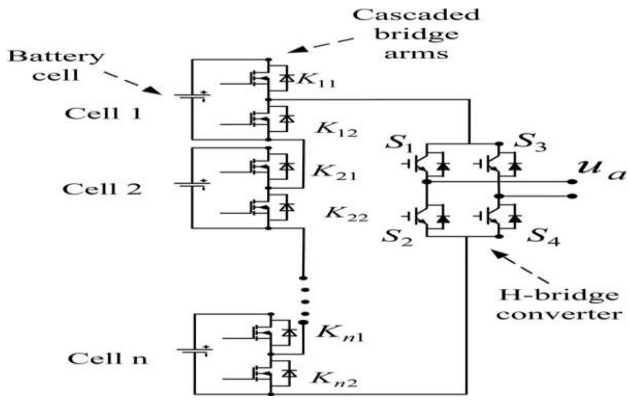

Figure 2. Hybrid cascaded multilevel converter.

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.

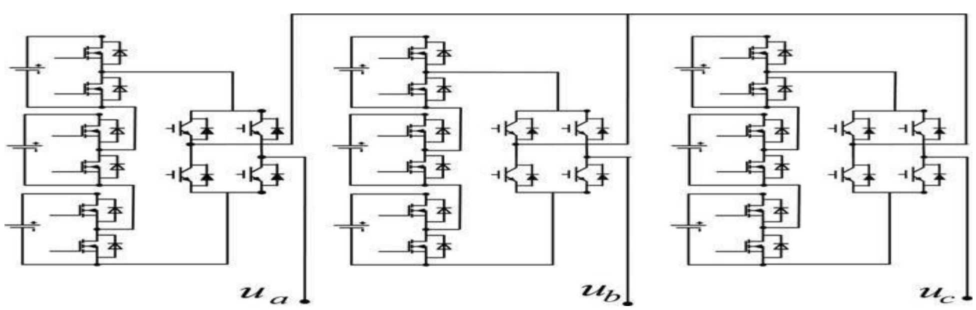

Figure 3. Three-phase hybrid cascaded multilevel converter.

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 numberof cascaded half-bridges in each phase.

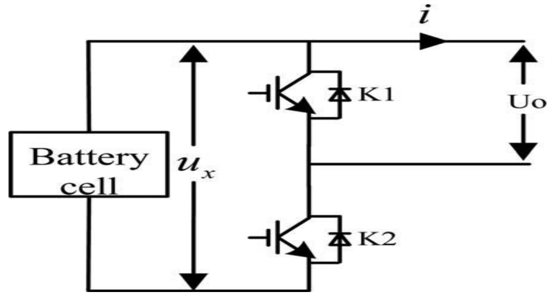

Figure.4. Output voltage and current of the battery cell

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.

3. CONTROL STRATEGY

3.1 CONTROL METHOD OF THE CONVERTER

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

S_X= 1upper switch is conducted, lower switch is OFF

S_X= 0 lower switch is conducted; upper switch is OFF.

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

$$P = S_X \cdot u_X \cdot i.$$

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 canbe improved while the overcharge and over discharged can be avoided. For the cascaded multilevel converters, generally there are two kinds modulationmethod: 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 modulationratio difference between different cells can be used for the balance control.

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 Sx= 1 or Sx= 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 toform the dc bus voltage with Sx= 1. The battery with lower terminal voltage or SOC will be controlled in switch state with $0 < mx < 1$ or be bypassed with Sx= 0. The control of the converter and voltage equalization can be realized by a modified carrier-cascaded PWM method. 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 usedless 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 theSOCis 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 usedinsteadof 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. 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, sothe carrier wave updated by base frequency is enough for the voltage and SOC balance. If the number of thecascaded cells is large enough, all then half-bridges can just work in switch-on or switch-off stateto form the staircase shape voltage. So, the switching frequency of all the half-bridges can onlybe base frequency, where the output ac voltage is still very approach to the ideal sinusoidal wave which is similar with the multilevelconverter in. When one cell is damaged, the half-bridge can bebypassed, 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-phasePWM can be adopted. The bypass method and the neutral shift PWM is very similar with the method.

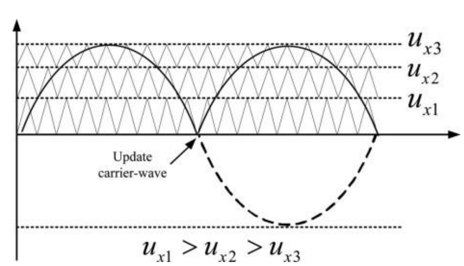

Figure 5. Carrier wave during discharging.

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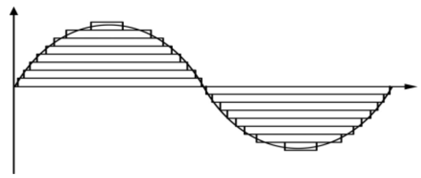

Figure 6. Base frequency modulation

3.1 LOSS ANALYSIS AND COMPARISON

Compared to the traditional circuit, the circuit topology and voltage balance process is quite different. In the traditional circuit, 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.

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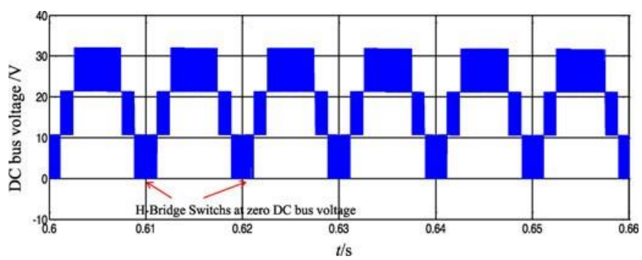

Figure 7 DC bus voltage output by the cascaded half-bridges

TABLE-1

Comparison of switching and conduction losses of the traditional and proposed converter

		loss in a single switching course	Conduction loss power
Traditional circuit	Energy transfer circuit	determined by imbalance	determined by imbalance
	3-phase inverter legs	J_{s_I}	$P_{c\_I} = I^2 R_{c\_I}$
Proposed novel circuit	Cascaded half-bridges	Much less than J_{s_I}/n	$P_{c\_B} = I^2 R_{c\_B} \cdot n$
	H-bridges	Near zero	$P_{c\_H} = I^2 R_{c\_H} \cdot 2$

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

$$P_{C-B} = I^2 R_{C-B} \cdot n$$

$$P_{C-H} = I^2 R_{C-H} \cdot 2$$

Here, I is the rms value of the output current, $R_{c\text{-}B}$ is the on-resistance of the MOSFET in the half-bridge, $R_{c\text{-}H}$ 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

$$P_{C-I} = I^2 R_{C-I}$$

where$R_{c\text{-}I}$ 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.

4. RESULTS

4.1 SIMULATION CIRCUIT:

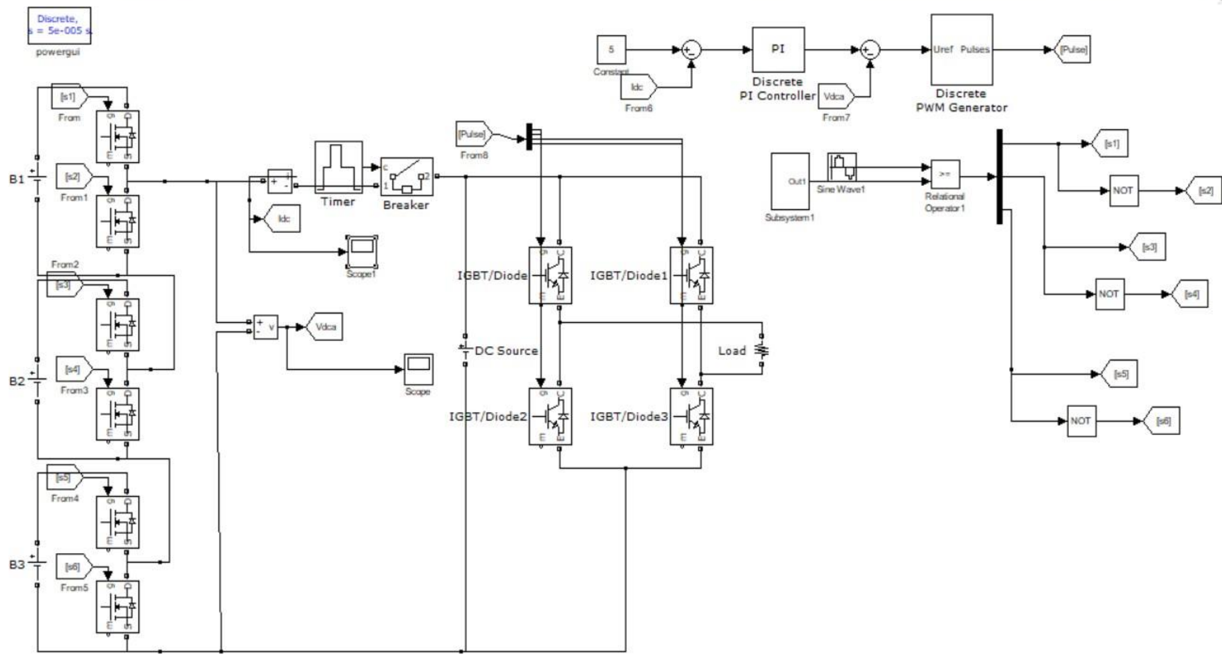

Figure 8 circuit model of hybrid cascaded multilevel inverter

4.2 SIMULATION RESULT:

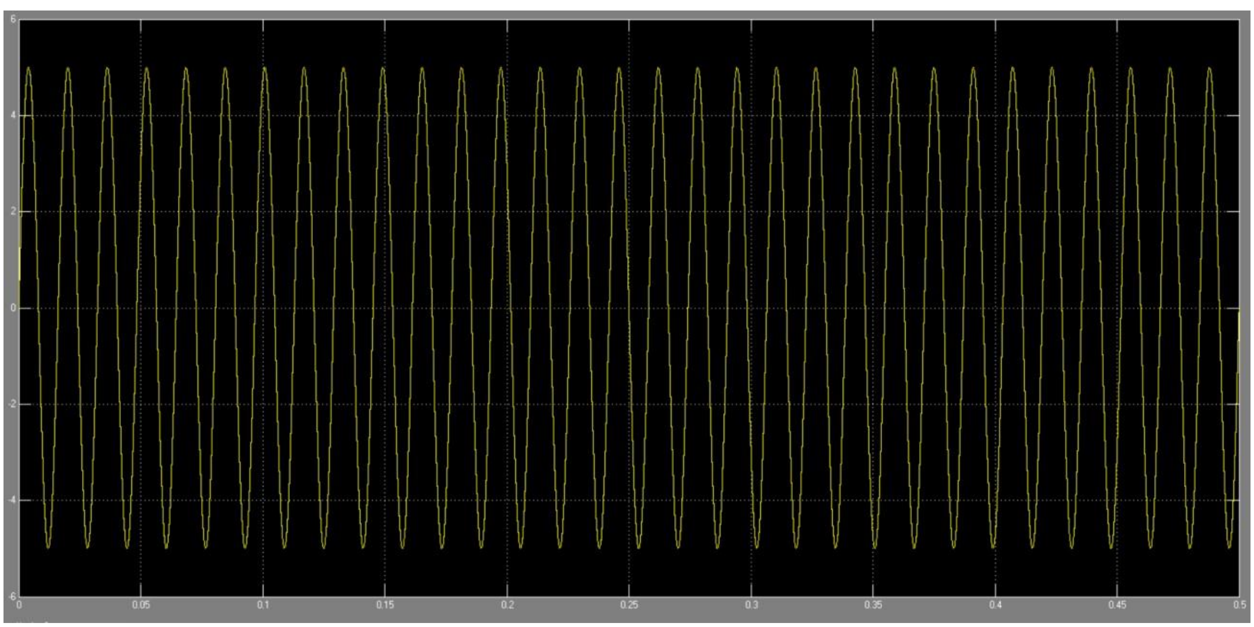

Figure 9 current wave form

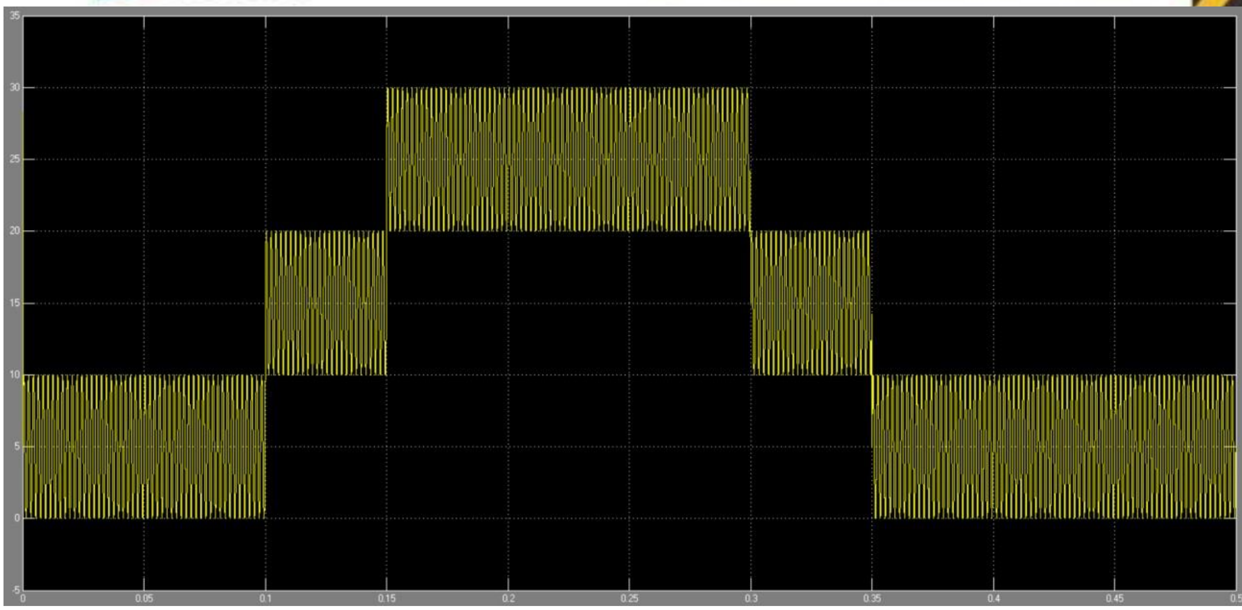

Figure 10 voltage waveform

5. 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.

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