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Hybrid Multi Modular Converter for 25 Level Inverter

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Abstract:
Energy storage system plays an important role in electric vehicles. In these 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 the existing system, a hybrid cascaded multilevel converter which involves both battery energy management and motor drives. 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. The imbalance of terminal voltage and SOC can also be avoided; Sso the life of the battery stack will be extended. In the proposed system, the level of the multi-level inverter can be increased to further reduce the total harmonic distortion without change in the circuit topology..

Keywords: Battery cell; charging and discharging; electric Vehicle (EV); hybrid cascaded multilevel converter; voltage balance

I. Introduction

The 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 [2], [3]. 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 practical applications to protect the battery cells from overcharging or over discharging.

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]–[8]. Some studies have been implemented to simplify the circuit and improve the balance speed by multistage equalization [7]–[9]. Some zero voltage and zero current switching techniques are also used to reduce the loss of the equalization circuit [10].

Multilevel inverters have been attracting wide industrial interest. They are considered an attractive alternative in order to reduce switch stress. The main characteristic of these converters is an output

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waveform with multiple voltage levels. In recent decades, an extensive array of multilevel structures has appeared for instance, the cascaded H-bridge, neutral point clamped, and flying capacitor. The Cascaded H-bridge multilevel inverter is a popular topology and has found widespread applications in industry, for instance, in high power medium-voltage drives and reactive power compensation. Most multilevel inverters have an arrangement of switches and capacitor voltage sources.

By a proper control of the switching devices, these can generate stepped output voltages with low harmonic distortions. These multilevel inverters are widely used in manufacturing factories and acquired public recognition as one of the new power converter fields because they can overcome the disadvantages of traditional pulse width-modulation (PWM) inverters.

A cascaded H-bridge multilevel inverter which employs one single dc input power source and isolated three-phase low-frequency transformers. By the proposed circuit configuration, a number of transformers can be reduced, compared with traditional three-phase multilevel inverters using single-phase transformers. Therefore, an economical and efficient inverter can be designed. Basically, the switching frequency of each H-bridge inverter is uniform with output fundamental frequency. The delay angles of each switch are calculated by the Sinusoidal pwm method on the basis of the area of each switch. All delay angles can be determined by applying the linearization method to each area. This approach is useful to eliminate low harmonic components of the output voltage.

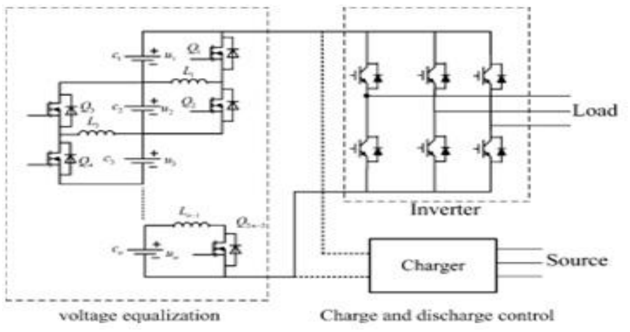

Fig. 1: Traditional power storage system with voltage equalization circuit and inverter

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.

II. TOPOLOGY OF THE MULTI-LEVEL CONVERTER

A. Hybrid Cascaded Multi Level Converter:

Multilevel converters are widely used in medium or high voltage motor drives. 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 the cascaded H-bridge converters are used for the voltage balance of the battery cells.

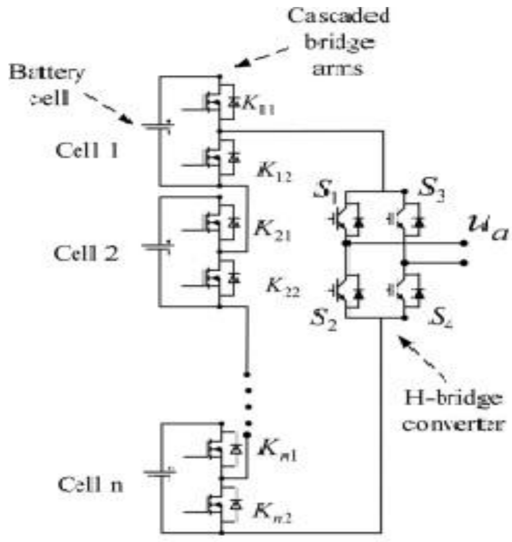

Fig. 2: Hybrid cascaded multilevel converter

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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. 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 which use fewer devices to realize the same output. Because of the power density limitation of batteries, some ultra-capacitors are used to improve the power density. Some converters must be used for the battery and ultra-capacitor combination. Multilevel converters with battery cells are also very convenient for the combination of battery and ultra-capacitors.

B. Three Phase Hybrid Cascaded Multi Level Converter:

A hybrid cascaded multilevel converter is proposed 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. Figure 2 represents the structure of a three-phase cascaded-type converter with separate dc sources. This type of converter does not need any transformer clamping diodes, or flying capacitors; each bridge converter generates three levels of voltages for a three-phase configuration, the cascaded converters can be connected in star or delta. It has the following advantages:

(1) It uses fewer components than the other types.

(2) It has a simple control, since the converters present the same structure.

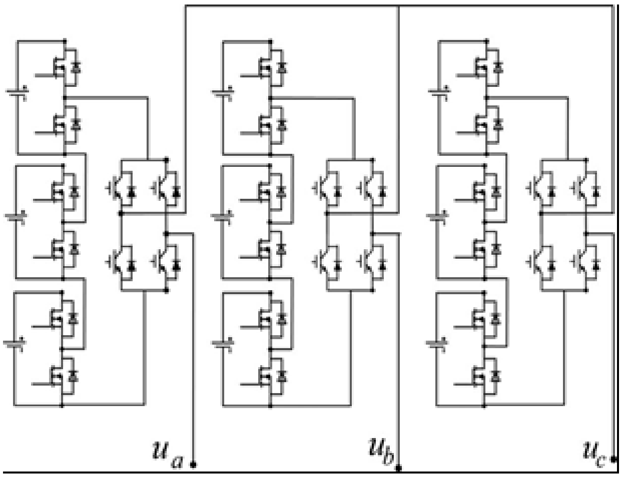

Fig. 3: Three Phase Hybrid Cascaded Multilevel Converter

The hybrid-cascaded multilevel converter includes two parts, the cascaded half-bridges with battery cells and the H-bridge Inverters. 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. 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.

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The three-phase converter topology is shown in Fig. 3.1. 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. The number of devices is not increased significantly but the inductances are eliminated to enhanced the system power density and EMI issues. 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.

C. Control Method of the Converter:

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

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

Sx = 0 lower switch is conducted, upper switch is OFF.

The modulation ratio mx 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.3.3, when Sx = 1, the battery is connected in the circuit and is discharged or charged which is determined by the direction of the external current. When Sx = 0, the battery cell is bypassed from the circuit, the battery is neither discharged nor charged. When 0 < mx < 1, the half-bridge works in a switching state. The instantaneous discharging power from this cell is P = Sx · ux · i.

Here ux is the battery cell voltage, i is the charging current on the dc bus, n is 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.

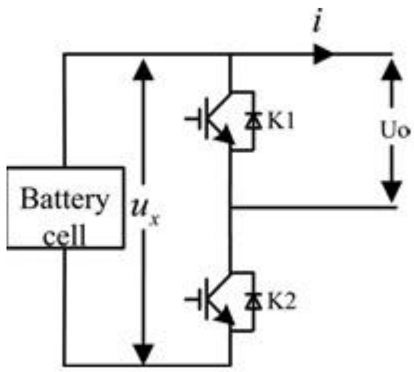

Fig. 4: Output voltage current of the battery and cell.

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. 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 to form 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 as shown in Fig. 3.3. 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

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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. So the carrier wave is only rearranged at most twice during one reference ac voltage cycle as shown in Fig. 5.

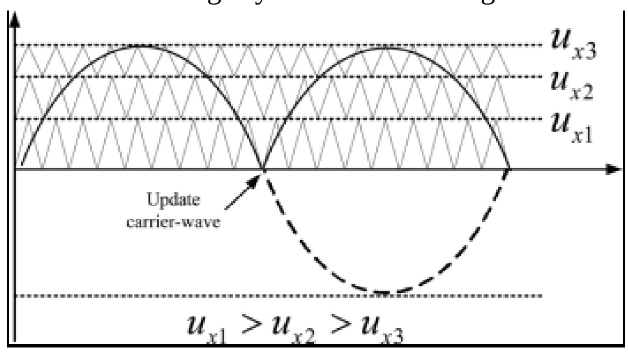

Fig. 5: Carrier wave during discharging

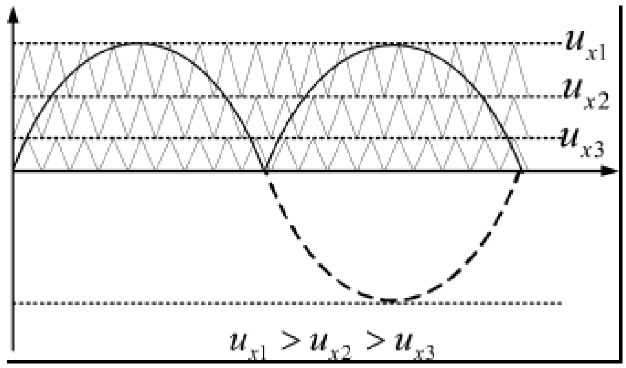

Fig. 6: Carrier wave during charging

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

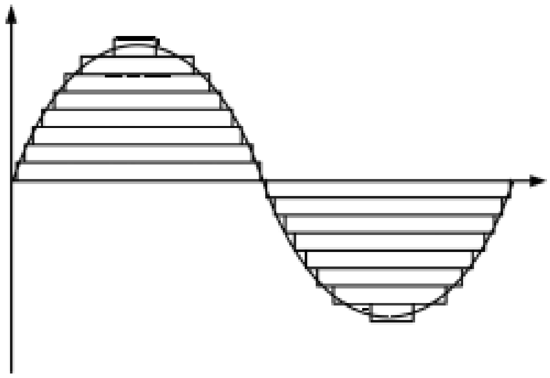

Fig. 6: Base frequency modulation

D. Charging Method:

In the system using the proposed circuit 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.7.

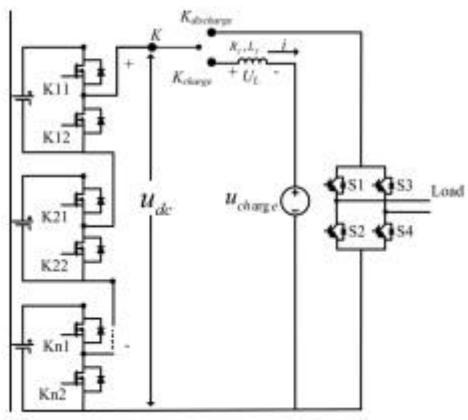

Fig. 7: Charging circuit of battery with dc source

A circuit breaker is used to switch the Fig. 7. Charging circuit of battery with dc source. Similarly the Fig.8. Shows the charging circuit of battery with ac source.

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. 3.8. The H-bridge worked as a rectifier by the diodes and a steady dc voltage is produced with the help of the capacitors. In the charging course of the battery, the charging current should be controlled. Fig

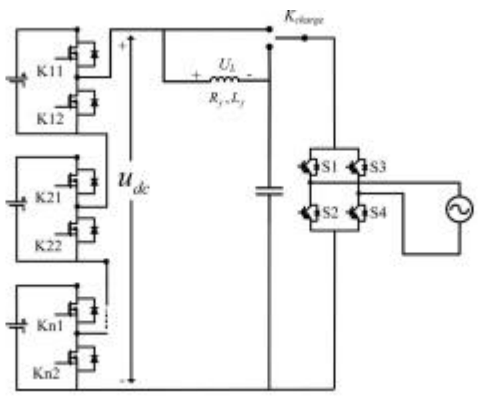

Fig. 8: Charging circuit of battery with ac source.

A circuit breaker is used to switch the Fig. 3.8. Charging circuit of battery with dc source. Similarly the Fig.3.9. shows the charging circuit of battery with ac source. 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. 3.8. The H-bridge worked as a rectifier by the diodes and a steady dc voltage is produced with the help of the capacitors. In the charging course of the battery, the charging current should be controlled.

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.3.10. That is similar to the fast-charge method of the battery to improve the intermittent charging current of battery cells.

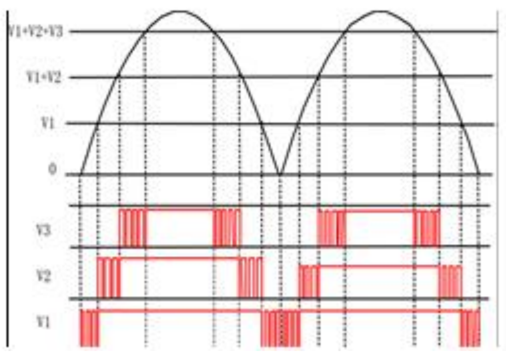

Fig. 9: Intermittent charging current of battery cells

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.

III. EXISTING SYSTEM SIMULATION

A. Existing System:

The MATLAB diagram of the existing system is shown in Fig. 10

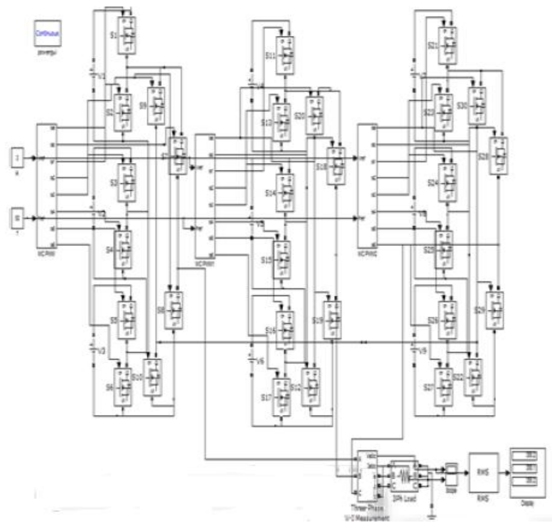

Fig. 10: Existing System

The above circuit shows the Simulation of three phase hybrid cascaded multi-level inverter. Each leg contains ten switches totally thirty switches needed for three phase. Here MOSFET act as a switch due to high frequency switching. Each legs having three voltage sources at same voltages. Pulse for MOSFET switch obtains from MCPWM technique. The output of the converter circuit having seven level.

B. Output Waveforms:

The voltage, current waveforms are shown in Fig. 10

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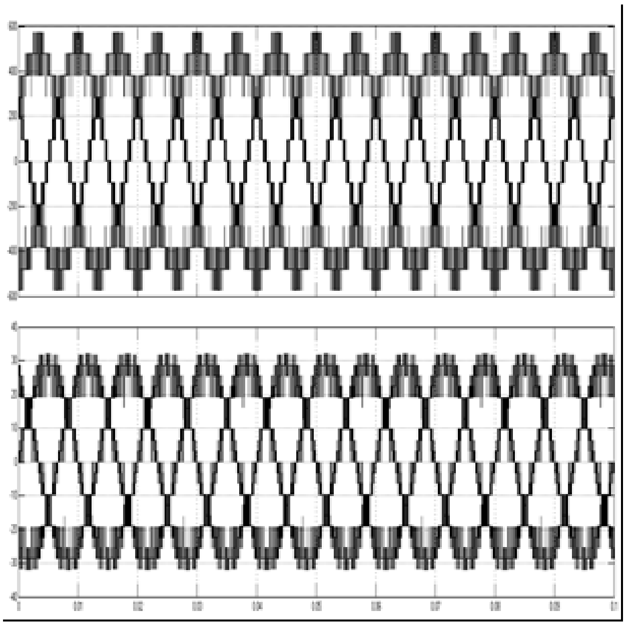

Fig. 10: Output voltage and current waveform.

Fig.10. shows the wave form of output voltage Vs time and output current Vs time. Voltage and current is taken in the y-axis and time in the x-axis. Here 600V is given as output voltage and 40A is output current.

The ac output voltage and output current are shown in Figs.10, which indicate the whole process from start-up to the stable state of the relative IM. It is obvious that the output voltage levels keep increasing according to the acceleration of the motor speed. 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.

C. FFT Analysis:

The below fig shows the FFT analysis of Existing system. Magnitude is taken in the y-axis and Frequency in the x-axis. Here Fundamental frequency (50Hz) =496.8 THD=14.68%

The FFT analysis result of the output ac phase voltage is shown in Fig. 10. It shows that the harmonics is little compared to the base-frequency component.

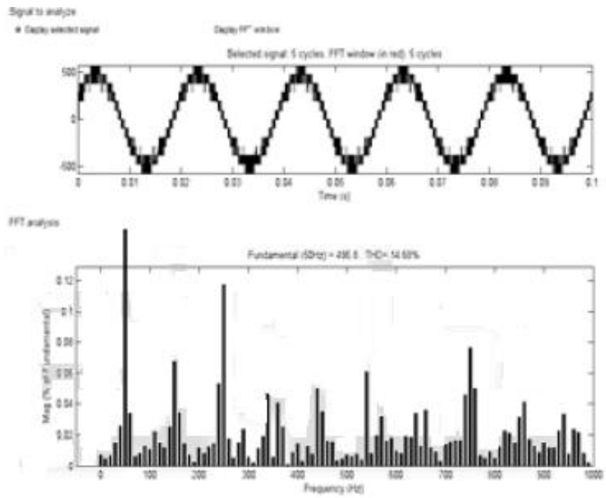

Fig. 11: FFT Analysis of Existing system

IV. PROPOSED SYSTEM SIMULATION

A. Proposed System:

The MATLAB diagram of the proposed system is shown in Fig. 12.

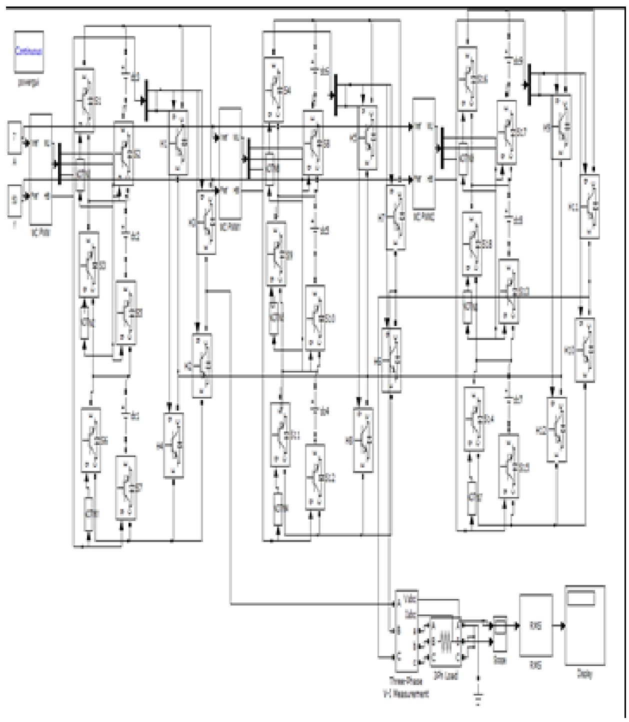

Fig. 12: Proposed system simulation

The above circuit shows the Simulation of three phase hybrid cascaded multi-level inverter. Each leg contains ten switches totally thirty switches needed for three phase. Here IGBT act as a switch due to high power application. Each legs having three voltage sources at same voltages. Pulse for IGBT switch obtains from MCPWM technique. 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.

The hybrid-cascaded multilevel converter proposed for 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.

B. Output Waveforms:

The output voltage, current waveforms are shown in Fig. 13

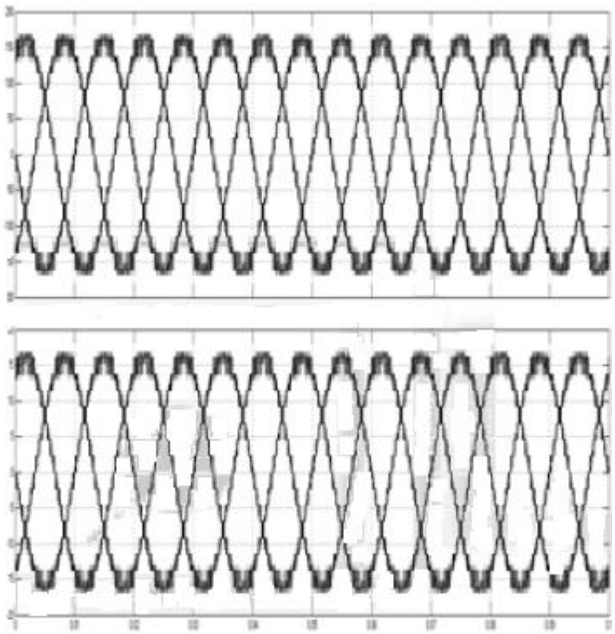

Fig. 13: Output voltage and current waveform

Fig.13 shows the wave form of output voltage Vs time and output current Vs time. Voltage and current is taken in the y-axis and time in the x-axis. Here 200V is given as output voltage and 20A is output current.

The ac output voltage and output current are shown in Figs. 13, which indicate the whole process from start-up to the stable state of the relative IM. It is obvious that the output voltage levels keep increasing according to the acceleration of the motor speed. The level of the output increases shows improved sinusoidal shape which can reflect the control performance of the motor. 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.

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.

C. FFT Analysis:

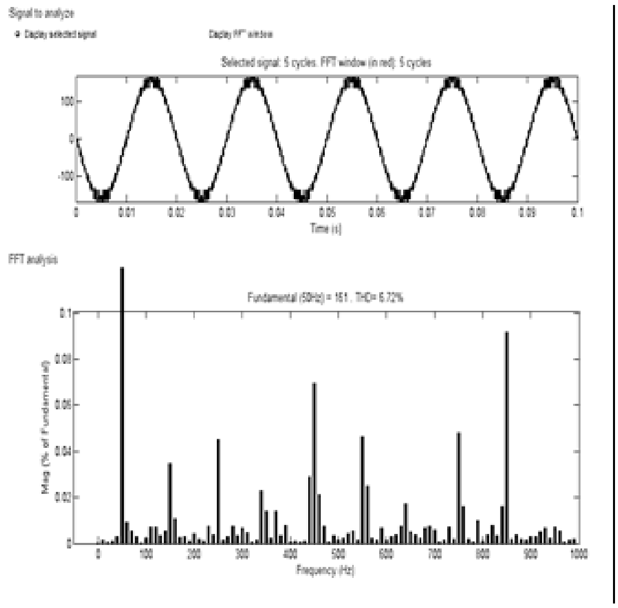

Fig. 13: FFT Analysis of Proposed System

Fig.13 shows the FFT analysis of Existing system. Magnitude is taken in the y-axis and Frequency in the x-axis. Here Fundamental frequency (50Hz) =161 THD=6.72%

The FFT analysis result of the output ac phase voltage is shown in Fig.13 It shows that the harmonics is little compared to the base-frequency component.

V. PULSE GENERATION CIRCUIT

A. Multi Carrier PWM:

Having more than two voltage levels to build a sinusoidal shape it is intuitive that we can have reduction of the current harmonics in the load. Nevertheless, the actual improvement of the current spectrum depends on the control technique

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employed. The most popular control technique for traditional inverters is the sinusoidal or "sub harmonic" natural pulse width modulation (PWM) method. Its popularity is due to its simplicity and to the good results it guarantees in all the operating conditions, including "over modulation," which allows first harmonic. A complete analysis of both bipolar (for two-level inverters) and unipolar (for three-level inverters) methods has been widely. We now develop a analysis of the MCPWM method for multilevel inverters. We refer to the system outlined in Fig.13 .For the proposed multilevel generalization of the PWM method; we take as a starting point the unipolar technique. The idea we follow is to use several triangular carrier signals, keeping only one modulating sinusoidal signal. If an N-level inverter is employed, N - 1 carriers will be needed.

B. Simulation of Pulse Generation Circuit:

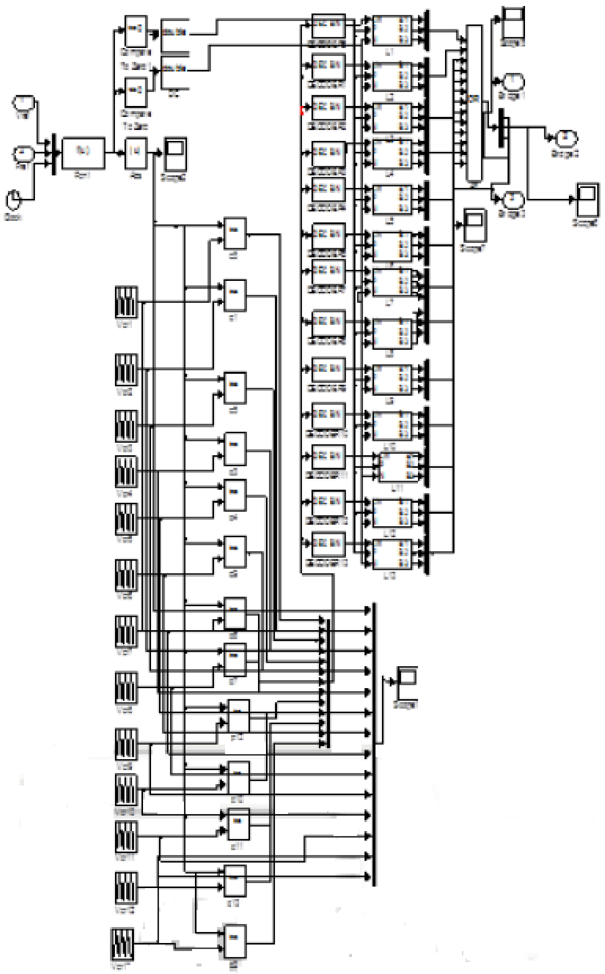

Fig. 14: Pulse Generation Circuit

C. Output Waveform of Pulse Generation Circuit

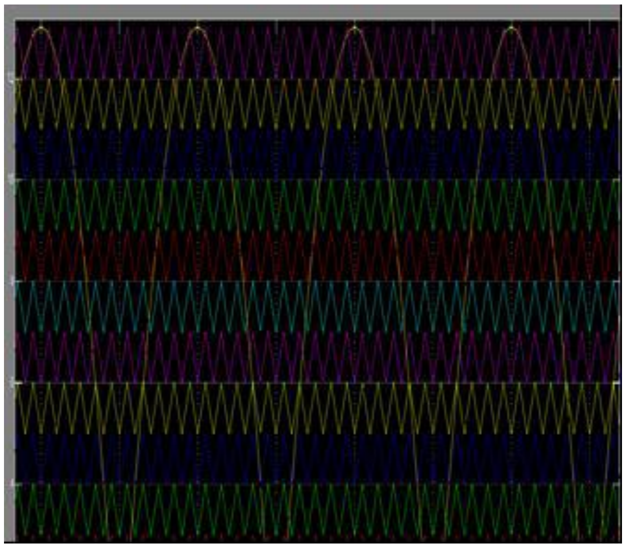

Fig. 15: Output waveform for pulse generation circuit

VI. CONCLUSION

A hybrid cascaded multilevel converter topology based on a small and cheap H-Bridge converter has been proposed, simulated and verified. 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 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 fifteen level 3phase proto type using Multicarrier Pulse Width Modulation Control was implemented to demonstrate some of its advantages: excellent voltage waveforms, THD reduces and, hence, almost perfect current waveforms. The proposed solution is Multilevel Inverters become a real solution for EV and traction applications.

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