A Hybrid Cascaded Multilevel Converter for Battery Vitality Administration Connected In Electric Transport for Battery Energy Management

Srinivas Gadde1, Bhanu Ganesh Lukka2 and Shankar Mahesh Kumar Gali3

123Department of Electrical Engineering, Vignan Institute Of Technology and Science (VITS) Deshmukhi, Yadadri,

Abstract. In the (EV) electrical vehicles energy storage system plays a crucial role. Normally, in electrical vehicles large number of cells connected in series to increase the output voltage for driving motor. Battery cells will have different electrochemical characteristics which cause the difference in terminal voltage (or) (SOC) state of charge imbalances between the each cell. In this paper cascaded multilevel converter which involves in both management of energy and motor drives proposed for electric vehicles and each battery cell can be controlled to the circuit or bypassed by a half-bridge converter. All these half-bridges are cascaded to the output staircase shape dc voltage. And H-bridge converter will be used to change the direction of dc bus voltage to convert it ac voltage. The advantage of the converter will have multilevel voltages with small dv/dt and lesser harmonics. So, it is helpful to make better performance of motor drives. Through separate control according to state of charge of each cell the energy utilization of batteries can be improved drastically. By using the fuzzy logic controller for current measurement the THD can be reduced drastically. In order to verify the performance of proposed converter simulation done in matlab.

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 [1-2]. 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. 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 [1]. The demerit is that it require lot of inductances and isolated multiple winding transformers in this topology and it leads to complexity in operation of converter [5]-[12]. So, some studies have been performed to simplify the circuit and also to improve balance speed by multiphase equalization [9]-[13]. Such as zero current and zero voltage switching also performed to reduce the loss of equalization circuit [13].

* Corresponding author: gadde.cnu@gmail.com

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The proposed Hybrid cascaded multilevel converter in this paper, it can realize the SOC or terminal voltage between the cells. The proposed converter can realize the discharging and charging control of the battery cells. And we get the desired AC voltage at the output of H-bridge converter 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.[1]

2 Hybrid Cascaded Multilevel Converter Topology

It is one of the most popular methods for voltage balancing circuit through energy transfer as shown in the figure.1 [5], [19] it consist of an Half bridge arm and inductance between the two cells. So, number of inductance is n-1 and number of switching devices are 2*n-1.where n stands for number of battery cells. And moreover, this circuit requires an additional inverter for the motor drive and a charger is required for recharging the battery. [1]

![Fig.3. Three phase hybrid cascaded multilevel converter.](image)

From the figure it is clear that output of the cascaded Half bridges is the dc bus is connected to the dc input of H-bridge. In the above circuit, each half bridge makes the battery cell involvement in voltage produced or bypassed to the circuit. H-bridge converter is equals to base frequency of desired alternating current voltage.[1]

![Fig.4. Output current and voltage of the battery.](image)

There are two kinds of power electronics devices are proposed in this circuit. MOSFETs and IGBTs [1].The proposed topology of three phase converter is shown in the figure.3. if ‘n’ number of battery cells used in each phase, then the number of devices used in H-bridge each phase is 2*n. when compared to explained in [1].

3 Control Method of the Converter

In the cascaded half bridges are defined by $S_{s1}=1$ upper switch is conducted and lower switch will be in off state.$S_{s2}=0$ lower switch is conducted and upper switch will be in off state. The modulation carrier wave is zero. Here carrier wave is rearranged when the modulation carrier wave is zero and rearranged carrier wave is zero. Here carrier wave is rearranged only two times during one reference voltage cycle as shown in the figure.5. The cells SOC and voltage vary slowly during normal usage soothe carrier wave updated by the base frequency is enough for SOC and voltage balance.

In order to reduce EMI and dv/dt here only one half bridge allowed to change the switching state at a same time continuous reference voltage. Hence, carrier wave is rearranged when the modulation carrier wave is arranged when the modulation carrier wave is zero and rearranged carrier wave is zero. Here carrier wave is rearranged only two times during one reference voltage cycle as shown in the figure.5. The cells SOC and voltage vary slowly during normal usage soothe carrier wave updated by the base frequency is enough for SOC and voltage balance.

![Fig.5. Carrier wave while discharging](image)

Here all the half bridges are worked at the base frequency as shown in the figure 6, where the alternating current output voltage is approaches to sinusoidal wave as similar to the multilevel converter [15].

![Fig.6. Base frequency](image)
If one of the battery cell got damaged, the half bridge is bypassed, and it will be no influence on the other battery cells. The output voltage of the bypassed battery cell is reduced. And we need to reduce the three phase reference voltage to fit to the output voltage ability. In order to improve the output voltage, the neutral shift three phase is adopted. Which is explained in [17-18].

4 Losses Analysis and Comparison

The circuit topology and voltage balance of the proposed circuit is quite different from the traditional circuit shown in the figure 4. In the traditional circuit method the energy transfer circuit used for the voltage balance and three phase two level DC-AC converter used for discharging control. In this proposed Hybrid cascaded circuit, discharging control is associated with the H-bridge converter and cascaded Half-bridges are used for voltage control. For this two circuits, the conduction losses and switching losses are quite different. In order to get clear thought, the conduction and switching losses are analyzed as follows:

\[ J_{\text{Loss}} = J_{C_B} + J_{C_H} + J_{S_B} + J_{S_H} \]  

Where \( J_{C_B} \) and \( J_{C_H} \) are conduction losses of cascaded half bridges and H-bridge converters and \( J_{S_B} \) and \( J_{S_H} \) are switching losses of Half bridge and H-bridge converter.

![Fig 7. Dc output voltage of the cascaded half bridges](image)

**Table 1.** Switching and conduction losses comparison of traditional and proposed circuit

| Circuit Type          | Energy transfer circuit | Conduction losses | Switching losses |
|-----------------------|-------------------------|-------------------|------------------|
| Traditional circuit   | Determined by imbalance | Determined by imbalance |
| 3-phase inverter      | \( J_{c/s} \)           | \( P_{c/s} = J_{c/s} \) |
| Proposed novel circuit|                        |                   |
| Cascaded half bridges | Much less than \( J_{c/s} \) | \( P_{c/s} = 1/2 \times P_{c/s} \) |
| H-bridges             | Near zero               | \( P_{s/s} = 1/2 \times R_{s/s} \times 2 \) |

5 Charging Method

In the proposed converter circuit, a dc voltage source is needed for charging the battery. The charging voltage and current can be controlled by the proposed circuit itself according to necessity of the battery cells. Circuit diagram of charging circuit is shown in the figure 8. In order to switch the dc bus from H-bridge the dc voltage source, a circuit breaker is used. Further, a filter inductor is also used in order to realize the current control, which is connected in the series. The dc voltage source can also be realized by using capacitor and H-bridge as shown in figure 9. Here H-bridge which is worked as a AC-DC converter i.e., rectifier by using diodes and a steady state dc voltage is produced by using capacitors. While charging the battery, the charging current needs to be controlled. The current state equation is

\[ R_i + L_i \frac{dx}{dt} + u_{\text{charge}} = 0 \]  

Where \( u_{\text{charge}} \) the voltage of dc source, \( u_{0} \) is the dc bus output voltage of cascaded Half bridge converter and \( L_i \), \( R_i \) are the inductance and resistance of the inductive filter between the dc source and cascaded Half bridges. In this charging method, the bus voltage must be smaller than that of the possible maximum value of the dc bus voltage.

\[ u_{\text{charge}} \leq u_{0} \leq u_{T} \]  

Where \( u_{T} \) is the discharging cut-off voltage of the battery cell and \( n \) is the number of cascaded half bridges in each phase.

![Fig 8. Charging circuit of cell with dc source](image)

While charging cycle their might be variation in the voltage of battery cells and the dc source voltage, to make the charging current constant and the switching states of cascaded half bridges are switched. Circuit of current control scheme is shown in the above figure 10.

![Fig 9. Charging circuit of cell with ac source](image)

A proportional integral (PI) controller is used to make the constant current by charging the dc output voltage of the cascaded cells. [1]

![Fig 10. Current control scheme for battery charging](image)

The arrangement of carrier wave in charging state is opposite to that of discharging state. The battery cells with higher voltages will be arranged in top levels in order to make them absorb less energy. Similarly, the battery cells with lower voltage are placed at the bottom to make them absorb more energy from the dc source.
During the discharging state similar analysis is performed and the positions of the carrier waves is shown in the figure 9. During the regenerative breaking mode of the motor drives i.e., when electric vehicles EV is breaking, the battery cells are charged, hence the modulation will be changed to charging state/mode as shown in the figure.11

Energy charged in the cell battery is same as the traditional one i.e., 
\[ P_{\text{Charge}} = U X_i S_x \]  
(5)
Here i is the charging current controlled by the scheme and S_x is the switching state of the bridge arms.

![Fig. 11. Carrier wave during charging](image)

Three phase output voltage is shown in the figure 14. In each phase there are nine levels and the waveform is more similar to ideal sinusoidal waveform than the traditional two-level inverter.

![Fig 14. Three phase output multilevel voltage](image)

**Table. 2. Induction motor parameters**

| Parameter      | Value   |
|----------------|---------|
| Rated power    | 0.55kW  |
| Rated line voltage | 380V  |
| Rated line current | 1.5A  |
| Rated frequency | 50Hz   |
| Number of pole pairs | 2      |
| Rated speed    | 1390rpm |

Three phase output voltage is shown in the figure 14. In each phase there are nine levels and the waveform is more similar to ideal sinusoidal waveform than the traditional two-level inverter.

![Fig 15. ac and dc output voltage while motor acceleration](image)

An induction motor driven with (VVVF) variable-voltage-variable-frequency control method is applied. The parameters of above induction motor is shown in given table.2

![Fig 16. Output dc and ac current while motor acceleration.](image)

The ac voltage, dc bus voltage, dc bus current, output are shown in figure15 and 16, it indicate that whole process from starting to stable state of induction motor. From the figure.15, it is clear that motor speed, its voltage levels are increasing. The stator current in the motor is shown in the figure.16 is a improved sinusoidal waveform, it will reflects the control performance of the motor.[1]. But, here the phase ac current will change its direction after certain period of time, hence the direction of dc bus is reversed when the current and phase voltage direction are different. [1]

6 Results of Experiment

In order to verify the performance of proposed converter and its control method, an three phase 3-cells cascaded circuit simulation done in matlab. It is shown in the figure 2. In this we used lead-acid battery module with 16.67v. Since, it is difficult to estimate the SOC of battery cells, the terminal voltages are used for the PWM carrier wave arrangement. Cascaded half bridges are designed with MOSFETs and H-Bridge designed with IGBTs.
The dc bus current is shown in figure 17 if there is some loads and it has some reverse current. This reverse current is greatly reduced by means of average power flowed from converter to the motor.

Figure 18 shows the dc bus current and dc bus voltage when the dc source was connected. It shows when dc source was connected. In the figure 17, there are two half bridges working at $S_x=1$ and third one working in switching state.

When the charging current reference given, the dc voltage reduce first to establish with dc current is shown in the figure 19. The resistance of the filter inductance is very small, the voltage drop on the filtered inductance through dc current is almost near to zero, and the dc bus voltage becomes same as non-charging state.

At the time of battery charging, if dc source voltage is charged, the charging current control results is shown in figure 20. As we did not used feed forward compensation in our system the output has some ripples during the course of time.

7 Proposed Work

7.1 FUZZY LOGIC CONTROLLER

A fuzzy control system it is based on fuzzy logic i.e., a mathematical system which takes input analog values in the form of logical variations, that takes continuous values between 0 and 1 compared to digital logic which can operate on discrete value either 0 or 1 i.e., false or true respectively.

Total Harmonic Distortion (THD) in the current measurement scheme is reduced to 1.39% by using fuzzy logic controller and THD present PI controller is 6.27%.

8 Conclusion

In the proposed paper, hybrid cascaded multilevel converters, can realize the discharging and charging by battery cells, while SOC or terminal voltage balance can be realized at same time. By its modular structure it is suitable for n number of cascaded levels and it also suitable for energy storage system with lower voltage battery modules or cells. If there is any fault in battery module it can be bypassed without affecting the other which are running, hence this converter has good fault controlling capability, so it can improve the reliability of the system. Here, we used dc current control method using fuzzy logic controller for battery cells charging and discharging with external using ac or dc is studied.
where additional charger is not required for constant current control. Simulation results are verified.

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