ABSTRACT: Voltage source inverter is commonly used as the interface to connect the renewable energy source and the power grid. In order to improve the performance of renewable energy system, the topology and control method of the inverter system need to be analysed. In this paper, a single-phase hybrid cascaded inverter is proposed. It is based on two kinds 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 and PWM carrier modulation methods are adopted in the paper. It is shown that the conversion efficiency reaches up to 98% and the output THD is less than 5% (meets requirement of the IEEE standards). Meanwhile, with different combination of switching states, the distribution of input active power in each H-bridge can be adjusted. As a result, for renewable energy system, larger control freedom is provided and the need of power balance is satisfied. The validity of the inverter system is tested by simulation.

Keywords: Renewable Energy System, Single Phase Induction Motor, Hybrid Cascaded Inverter.

I. INTRODUCTION

Energy and environment problem has received great attention all around the world. As a result, renewable energy is generally welcomed by the public for the characteristics of pollution-free and reserve-abundant [1-3]. To meet the self-requirement of high efficiency and high reliability for the renewable energy source, the performance of the power electronics interface should be improved [3, 4]. Suitable topology and control method are needed to reach the high-level operation. The research work in the paper is focused on the DC-AC part in the renewable energy system. Based on the conventional structure of cascaded H-bridge inverter, a new kind of hybrid cascaded inverter (HCI) is accomplished. The hybrid structure is shown in two aspects. Firstly, the DC buses have hybrid voltages. They are V0, 2V0 and 4V0 respectively. Secondly, hybrid power devices are adopted. For DC buses with different voltages are employed, more voltage levels can be reached at the AC side, with rather lower switching frequency. As a result, the output harmonic loss and the switching loss are lower down. At the same time, for different kinds of power switches are employed, the performance of the inverter system can be further improved. According to the selected modulation method, the switching frequency in the three H-bridges are different. In V0 H-bridge, the DC bus voltage is lower and the switching frequency is higher, so power MOSFET is adopted. On the other hand, in 2V0 and 4V0 H-bridges, the DC bus voltage is higher and the switching frequency is lower, so IGBT is adopted. With the above combination of power switches, the advantages of different devices can be shown and the system loss is further reduced. The high efficiency operation of the inverter system can be reached. Compared with conventional two-level inverter, HCI has several advantages. They're flexible choice of devices, low voltage rating for each power switch, low output harmonic content, low switching frequency and so on. At the sametime, it should be emphasized that with the
rapid progression of renewable energy generation system, the concept of ‘Micro-grid’ is highly concerned worldwide [5-7]. ‘Microgrid’ includes several micro-sources inside and the above-structure of HCI has several DC input ports. As a result, HCIs are suitable for the application of Micro-grid. Its DC side can be easily connected to the micro-sources with DC voltage output. In this paper, a 2kW single-phase HCI is implemented. Its based on low-loss MOSFET (offered by IXYS Co.) and V-IGBT (offered by Fuji Electric Co.). Voltage gradational and PWM carrier modulation methods are employed. Therealization process of the two methods is shown theoretically. The structure of HCI and the two modulation methods are validated by simulation.

II. STRUCTURE OF HCI AND ITS MODULATION METHOD

The structure of the HCI is composed of three H-bridges, as shown in Fig. 1. They have isolated DC buses and the voltages are V₀, 2V₀ and 4V₀ respectively. And at the AC side, three H-bridges are connected in series. Concretely, V₀ H-bridge is based on MOSFET, while 2V₀ and 4V₀ H-bridges are based on V-IGBT. In the paper, two kinds of modulation methods are employed. First is voltage gradational method and second is PWM carrier method. 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 analysed 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 = x·V₀ + y·2V₀ + z·4V₀’, ‘V = (-1)·V₀ + 1·2V₀ + 0·4V₀’ and ‘V = (-1)·V₀ + (-1)·2V₀ + 1·4V₀’. 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).

\[ V = x \cdot V_0 + y \cdot 2V_0 + z \cdot 4V_0 \]  

(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. Finally, confirm the concrete output voltage of each H-bridge and the concrete state of each power switch. In order to lower down the contents of low frequency harmonic components, PWM carrier modulation method is employed. In this method, the outputs of 2V₀ and 4V₀ H-bridges are kept same as voltage gradational method. The sum of the above two output voltage waveforms has seven level staircase. The ideal sinusoidal waveform minus these seven-level staircase waveform reaches the modulation wave in V₀ H-bridge. So, PWM method is employed and the sum of the output waveforms in three H-bridges approximates to the ideal sinusoidal wave. Also, suppose V is the object voltage at the AC side, as shown in (1). With PWM carrier modulation method, in the positive half period, the coefficients y and z are confirmed as shown in (2). From (2), the output of 2V₀ and 4V₀ H-bridges are reached. The corresponding output voltage in V₀ H-bridge is got by the comparison of the above modulation wave and triangle carrier wave.
III. POWER BALANCE CONTROL METHOD IN HCI

As mentioned in Part II, in voltage gradational modulation method, there are several redundant superposition methods. The redundant states can be utilized. As commonly known, one H-bridge can output three kinds of voltages. They’re positive DC bus voltage, negative DC bus voltage and zero. Suppose the direction of the load current is shown in Fig. 2 (When the direction of the load current changes, the same analyzing process can be reached.). When positive voltage is reached at the AC side, the DC bus provides active power and the capacitor is discharging. At the same time, when negative voltage is reached, the DC bus absorbs active power and the capacitor is charging. When zero voltage is reached, no active power is transferred in the DC bus capacitor. HCI has several DC input ports. In the actual application, the DC bus can be connected to different kinds of sources. For example, it can be connected to photovoltaic (PV) panel, storage battery, and so forth. As known that, storage battery can store energy when the input energy is adequate in the inverter system, such as sufficient light for PV system. On the other hand, it can release energy when the input energy is inadequate. As a result, with different external conditions, the distribution of active power at the DC side should be adjusted accordingly. Take the following system as an example. The DC buses of V₀ and 2V₀ H-bridges are connected to storage battery and the DC bus of 4V₀ H-bridge is connected to PV panel. When sufficient sunlight is received in the system, 4V₀ H-bridge should provide more active power, while at the same time, V₀ and 2V₀ H-bridges should absorb active power and store energy.

When no enough sunlight is received, 4V₀ H-bridge should provide less active power and the other two bridges with storage batteries should provide more. The above power balance process is reached by selecting different superposition methods. Also, when starting up HCI, the DC bus capacitor should be precharged. It can be simply accomplished by selecting different superposition methods. Also take the above situation as an example. When starting up the HCI, the precharging process can be reached by selecting the superposition method of \((x, y, z) = (-1, -1, 1)\). Here, \((x, y, z)\) represents the concrete superposition method. It means that \(V₀\), \(2V₀\) and \(4V₀\) H-bridges output negative, negative...
and positive DC bus voltage. So the active power in 4V0 H-bridge flows to the V0 and 2V0 H-bridges. Three DC bus capacitors are precharged by the PV panel connected to 4V0 DC bus.

\[ m = \frac{U_{ac}}{U_{dc1} + U_{dc2} + U_{dc3}} \]  

(3)

IV. SIMULATION RESULTS

In order to verify the feasibility of the hybrid cascaded structure and the two modulation methods, simulation model based on MATLAB/SIMULINK is implemented. In the model, three H-bridges are adopted. The structure is as same as mentioned above. Furthermore, a 2kW prototype is built up, as shown in Fig.3. In both simulation, the load voltage of 220V (rms) is set up and inductive load of 15mH 200Ω is adopted. The output frequency is 50Hz. The AC output waveforms with the two modulation methods are shown in Fig.4 and 5. From Fig.4 and 5, it can be seen that both methods can reach staircase voltage waveform at the AC side. Concretely, the simulation FFT analysis results of AC output voltage are shown in Table I (without filtering).

![Fig.3: Simulink model of proposed converter](image-url)
HCI as follow in (3). Here, ‘m’ represents voltage utilization ratio. \( U_{dcx} \) \((x=1,2, 3)\) represents DC bus voltage. \( U_{ac} \) represents the rms value of AC voltage. So, in simulation, with voltage gradational method, \( m \) equals to 0.71, while with PWM carrier method, \( m \) equals to 0.65. And in experiment, with voltage gradational method, \( m \) equals to 0.76, while with PWM carrier method, \( m \) equals to 0.68. It can be concluded that simulation results are approximately in accordance and voltage gradational method has higher voltage utilization ratio than PWM carrier method. In order to reach higher energy conversion efficiency, it is required to evaluate the conversion efficiency.

In HCI, low-loss MOSFET offered by IXYS Co. and V-IGBT offered by Fuji Electric Co. are employed. The simulation efficiency evaluation process can be summarized as follow. Firstly, the analytical expression of each kind of power loss is confirmed, including the undetermined coefficients. Secondly, according to the datasheet, confirm the above undetermined coefficients by curve fitting. Finally, calculate each kind of power loss and conversion efficiency. Concretely, to IGBT, the steady state loss, turn-on loss and turn-off loss are expressed by (4) ~ (6). To MOSFET, the steady state loss and transient state loss (the turn-on and turn-off loss are unified as transient loss) are expressed by (7) and (8). The steady state loss of the free-wheeling diode in both bridges is expressed in (9) and the reverse recovery loss of the free-wheeling diode in IGBT bridge is expressed in (10).

\[
W_{\text{conT}}(t) = (u_{0T} + r_{0T}i(t))^\text{BconT} \cdot i(t) \cdot t_s
\]  
\[
W_{\text{onT}}(t) = A_{\text{onT}} i(t)^\text{BonT} \cdot V_{CC} / V_{\text{ref}}
\]  
\[
W_{\text{offT}}(t) = A_{\text{offT}} i(t)^\text{BoffT} \cdot V_{CC} / V_{\text{ref}}
\]  
\[
W_{\text{conMOS}}(t) = i^2(t) \cdot R_d \cdot t_s
\]
Fast-recovery diode is adopted as the free-wheeling diode in MOSFET bridge and the time-span of the reverse recovery process is further less than that in IGBT bridge. As a result, the reverse recovery loss of the free-wheeling diode in MOSFET bridge is ignored. Here, ‘WconT’, ‘WonT’ and ‘WoffT’ are the steady loss, turn-on loss and turn-off loss of IGBT respectively, ‘WconMOS’ and ‘WtranMOS’ are the steady loss and transient loss of power MOSFET. ‘WconD’ is the steady loss of free-wheeling diode in both bridges and ‘WrrD’ is the reverse recovery loss of free-wheeling diode in MOSFET bridge. ‘Vcc’ is the actual DC bus voltage and ‘Vref’ is the DC bus voltage shown in the datasheet; ‘i’ is the current flowing through the power switch. ‘Rd’ is the on-state resistor of MOSFET. In (8), ‘uDS’ is the voltage across terminal ‘D’ and ‘S’ when MOSFET is turned off and ‘iD’ is drain current when MOSFET is turned on. At the same time, ‘ttran’ is the time-span of the turn-on or turn-off process. In (4), (7) and (9), ‘ts’ is the control period. The other parameters are the undetermined coefficients. Then, according to the datasheet of V-IGBT and low loss MOSFET, by curve-fitting, the undetermined coefficients can be reached, as shown in Table I. So, the system power loss and efficiency can be achieved.

Fig. 5: Main winding current, Rotor current, Rotor speed, Torque developed
The simulation evaluation result is shown in Fig. 6. It can be seen that both methods realize high conversion efficiency (>98%) and voltage gradational method gets a higher efficiency than PWM carrier method. It is because with voltage gradational method, the highest switching frequency is 700Hz (in V0 H-bridge), while with PWM carrier method, the highest switching frequency is 10kHz (also in V0 H-bridge). No high frequency switching process is involved in voltage gradational method and switching loss is further lowered down. The experiment results of conversion efficiency can be shown as follow. With voltage gradational method, the experiment efficiency is 94.4% and with PWM carrier method, the result is 96.4%. The corresponding simulation results to the above experiment results are 97.6% (with voltage gradational method) and 96.4% (with PWM carrier method). It can be seen that the experiment results are slightly smaller than the simulation results. It is because that line impedance isn’t considered in simulation and the measurement error caused by the probe cannot be completely eliminated. It should be noticed that the output power and voltage level are kept same in both experiment results above, although for safety, the power level is smaller than that in Fig. 4.

In order to verify the power balance performance, different kinds of AC voltage superposition methods are tested. Take three situations as examples, shown in Table I. To each H-bridge, ‘psv0’, ‘ps2v0’ and ‘ps4v0’ represent the active power provided by the front micro-source in each H-bridge; ‘pinvv0’, ‘pinv2v0’ and ‘pinv4v0’ represent the active power transferred to the load. The values of above parameters in the three situations are shown in Fig. 5. It can be concluded that with different voltage superposition methods, the power distribution at the DC side can be changed. The operation of HCI is more flexible.

### Table I: Low Frequency Harmonic Contents of AC Voltage (Without Filtering)

<table>
<thead>
<tr>
<th>Voltage Gradational Method</th>
<th>PWM Carrier Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Freq./Hz</strong></td>
<td><strong>DC</strong></td>
</tr>
<tr>
<td>Simulation/%</td>
<td>0</td>
</tr>
</tbody>
</table>

**V. Conclusion**

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 H-bridge, power MOSFET is adopted while in 2V0 and 4V0 H-bridges, IGBT is employed. The advantage of each kind of device can be shown. The HCI is composed of three H-bridges. The DC voltage of each 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 and PWM carrier modulation methods are adopted and discussed in detail in the paper. Based on the simulation results, it can be concluded that high conversion efficiency (>98%) and good output performance (THD < 5%) of HCI are reached. And with different combination of switching states, the distribution of input active power at the DC side can be adjusted.

**REFERENCES**


BIOGRAPHY

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