International Journal of Advanced Information Science and Technology (IJAIST) ISSN: 2319:268
Vol.2, No.6, June 2013 DOI:10.15693/ijaist/2013.v2i6.30-36

A Novel Method For Capacitor Voltage Balance In Five Level Diode Clamped Inverter

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Abstract-The voltage source multilevel inverters synthesize the staircase waveform from several levels of dc capacitor voltages. Among the basic multilevel inverters diode-clamped multilevel inverters are widely used in high power applications because of their simple control techniques compared to other topologies. The diode-clamped multilevel inverter topology has the problem of voltage unbalance of dc link capacitors. This can be solved by using separate dc sources, or adding auxiliary circuits or adopting space vector modulation control in three-level inverter applications. For higher level applications, the use of separate dc sources is not viable and the control techniques for other two methods will be more complicated to implement. Hence the Hybrid Multilevel Inverter Based on Switched-capacitor and Diode-clamped units can be used for higher levels. Single leg of this topology consists of switched-capacitor part, that balances the capacitor voltage as well as step up the output voltage, and diode-clamped part. The boosting of output voltage contributes to lessen the transformation ratio of the input transformer or even eliminate it, thereby reducing the cost, which will benefit the design of converters in medium-high voltage applications. The topology is simulated using MAT lab simulink software and it is observed that the output voltage is stepped up and the capacitor voltages are balanced.

Keywords: Diode clamped inverter, multilevel inverter, pulse width modulation, switched-capacitor converter.

I. INTRODUCTION

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. Recently, multilevel inverters have drawn tremendous interest in the field of high-voltage and high-power applications because it has some advantages: it can realize high voltage and high power output through low-voltage switches without transformer and dynamic voltage balance circuits, with increased output level, reduced harmonics and EM1 are decreasing. Multilevel inverters are mainly classified as diode-clamped, capacitor-clamped and cascaded H-bridge inverters.

Among the basic multilevel inverters the problem of voltage unbalance of dc link capacitors exists inherently in the diode-clamped inverter topology, which limits the further application of it, especially at the level above three. To balance the voltage of dc link series capacitors, three main approaches have been proposed . They are: 1) using separate dc sources, [3],[4] 2) adding some auxiliary balancing circuits [5],[6] and 3) improving the control method by selecting redundant switching states [7],[8]. By auxiliary circuits, the transferred current or power can be controlled accurately, but the additional feedback control strategies are also needed, so the control of these converters becomes more complicated, and inverters are less reliable.

For three-phase multilevel inverters with the Space Vector Pulse Width Modulation (SVPWM) method some redundant states can be selected to balance dc link capacitor voltages without any auxiliary circuits. However, the SVPWM method works only in a low modulation index range, and results in degradation of output voltage quality. On the other hand, the control algorithm complexity of the SVPWM method is increased dramatically with the increase of level number. Cascaded H-bridge inverter uses separate DC sources for each H-bridge. This inverter is not viable while considering for higher level. The size and weight will also increases with increase in number of levels. Hence for higher levels more suitable approaches are still needed.

The recent trend is to use hybrid-clamped topology for voltage balancing. The concept of hybrid-clamped method is, using two or more types of clamping devices in one topology. The 3phase Hybrid Multilevel Inverter Based on Switched-capacitor and Diode- clamped (HMI-BSD) units is the combination of switched capacitor converter and four level diode clamped inverter. The most important advantage of HMI-BSD topology is the realization of self balancing of dc link capacitors without complicated auxiliary circuit or control strategy, especially for a five-level inverter or n-level (n > 5) inverter. Another important advantage of the HMI-BSD topology is the realization of the stepping up of output voltage, which contributes to lessening the transformation ratio of the input transformer, thereby reducing the cost, even to eliminate the input transformer, which will benefit the design of converters in medium-high voltage applications.

II. HMI-BASED ON SWITCHED CAPACITOR AND DIODE-CLAMPED UNIT

Fig.1 shows the block diagram of HMI-BSD. DC supply is given as the input and the HMI-BSD topology consists of two parts namely switched capacitor part and diode-clamped part. The switched capacitor part is a dc to dc converter and it provides the dc link voltage for diode-clamped inverter part. The load is connected to the output of inverter section.

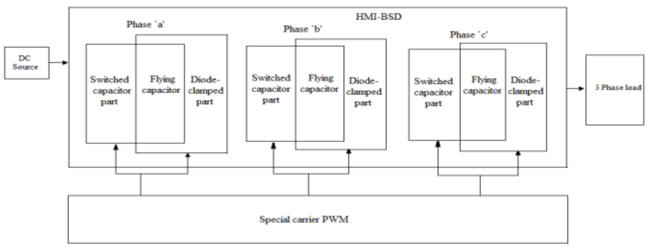

Fig.1 Block Diagram of HMI-BSD

From Fig.1 it can be observed that the flying capacitors are common to switched capacitor part and diode-clamped part. The control strategy of the switching devices of the switched-capacitor circuit is identical to that of the main switching devices, which means adopting the switched-capacitor circuit will not increase the complexity of control method regardless of the number of output levels. The circuit diagram of three-phase topology is deduced by combination of three HMI-BSD single-leg circuits sharing common dc link capacitors, shown in Fig.2 . All the elements sustain the same voltage stresses, which equal 1/(n-1)of the dc link voltage.

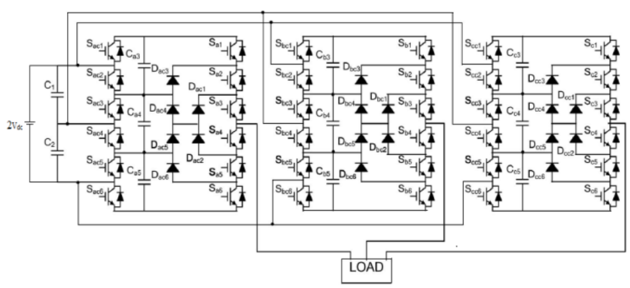

Figure 2: Three Phase Five-level HMI-BSD

The HMI-BSD can be easily expanded to any multilevel converter with n levels ($n \geq 4$). For an n-level HMI-BSD converter, each leg contains (2n-5) capacitors, including (n-3) dc link capacitors and (n-2) flying capacitors; 4 x (n-2) switching devices, including 2 x (n-2) main switching devices and 2 x (n-2) clamping switching devices; (n-2) x (n-3) clamping diodes. All the capacitors sustain the same voltage, and all the switching devices and clamping diodes have the same voltage stresses.

A. PRINCIPLE OF OPERATION

A single-leg five-level inverter topology based on HMI-BSD is shown in Fig.3. The topology can be divided into two parts, which are, respectively, indicated by a dash dotted frame and a dashed frame. Part 1 is called switched-capacitor part and part 2 is called diode-clamped part. The switched-capacitor part is composed of the dc link capacitors (C_1 , C_2), the flying capacitors (C_3 , C_4 , C_5), and the clamping switching devices (S_{c1} S_{c6}). And the diode-clamped part is composed of the flying capacitors (C_3 , C_4 , C_5), the clamping diodes (D_{c1} D_{c6}), and the main switching devices (S_1 S_6). It can be seen clearly that both parts include the flying capacitors C_3 , C_4 , and C_5 .

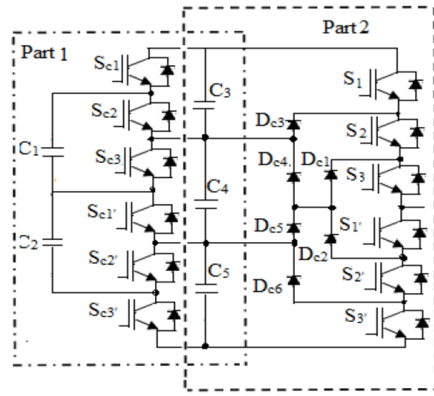

Figure 3: Single-leg of Five-level HMI-BSD

The diode-clamped part is a classical four-level diode-clamped topology with four kinds of working states and four kinds of output voltage levels. All the working states and their bilateral transitions of this part are shown in Fig.3. Among the main switching devices S_1 S_6, only three switching devices in succession are switched on in each working state. And (S_1, S_4), (S_2, S_5), and (S_3, S_6) are complementary switching pairs. In Fig.4, the arrows indicate the owing directions of the positive or negative current. The switched-capacitor part operates with two kinds of working states. The clamping switching devices S_{c1} S_{c6} can be divided into two groups: Group A and Group B.

Group A includes S_{c1}, S_{c3}, and S_{c5}, and Group B includes S_{c2}, S_{c4}, and S_{c6}. The control signals for the switching devices of the same group are identical. When the switching devices of Group A are switched ON, those of Group B are switched OFF, and vice versa. The switching devices of the two groups are switched ON or OFF alternately, as shown in Fig.5 . If the switching devices of Group A are ON and those of Group B are OFF C_1 is paralleled with C_3, and C_2 is paralleled with C_4.

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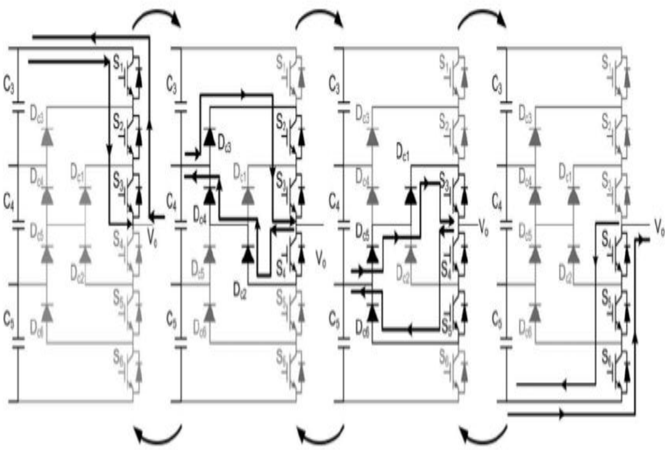

Figure 4: Diode Clamped Part of Five-level HMI-BSD

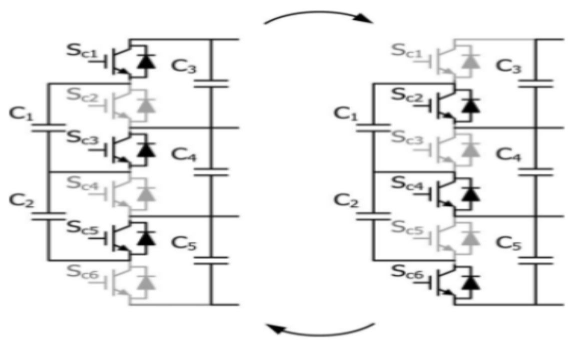

Figure 5: Switched Capacitor Part of Five-level HMI-BSD

If taken the dc link capacitors as a voltage potential reference, the voltage potentials of the flying capacitors are decreased by one level in this case. If the switching devices of Group B are ON and those of Group A are OFF C_1 and C_4, C_2, and C_5 are in parallel, respectively, the voltage potentials of the flying capacitors are lifted up by one level. If four kinds of working states of the diode-clamped part are combined with two kinds of working states of the switched capacitor part, eight kinds of working states of HMI-BSD can be obtained. Every working state corresponds to one kind of output voltage level.

Table 1 shows the relationships between the output voltage Vo and the working states, where U_{dc} is the voltage of one dc link capacitor. The switched-capacitor part not only contributes to balance the dc link capacitors, but also participates in the synthesis of the output voltage levels by the common connection of the flying capacitors with the diode-clamped part. In this case, the HMI-BSD can output five kinds of voltage levels with only a conventional four-level diode-clamped topology.

TABLE 1: RELATIONSHIPS BETWEEN THE OUTPUT VOLTAGE V_0 AND THE WORKING STATES

No. of working states	Output level V_o	S_1	S_2	S_3	S_4	S_5	S_6	Group A	Group B
1	$+2V_{dc}$	1	1	1	0	0	0	0	1
2	$+1\ V_{dc}$	1	1	1	0	0	0	1	0
3		0	1	1	1	0	0	0	1
4	$0\ V_{dc}$	0	1	1	1	0	0	1	0
5		0	0	1	1	1	0	0	1
6	$-1\ V_{dc}$	0	0	1	1	1	0	1	0
7		0	0	0	1	1	1	0	1
8	$-2\ V_{dc}$	0	0	0	1	1	1	1	0

B. VOLTAGE BALANCE OF CAPACITORS

If only the diode-clamped part of the HMI-BSD works without the switched-capacitor part, the voltages of capacitors, including dc link capacitors and flying capacitors, would be unbalanced due to the asymmetric charge current and discharge current through capacitors, which also happens with the conventional diode-clamped topology. The switched-capacitor part plays a role in balancing the voltages of capacitors by alternative conduction of the clamping switches Sc_1 - Sc_6. When the switching devices of Group A are ON and those of Group B are OFF, C_1 and C_3, C_2 and C_4 are in parallel, respectively, so $V_{C1} = V_{C3}$ and $V_{C2} = V_{C4}$.

When the switching devices of Group B are ON and those of Group A are OFF, C_1 and C_4, C_2 and C_5 are in parallel, respectively, so $V_{C1} = V_{C4}$ and $V_{C2} = V_{C5}$. If the switching devices of Group A are turned from ON to OFF, and from OFF to ON over and over again, then $V_{C1} = V_{C2} = V_{C3} = V_{C4} = V_{C5}$. That is to say, each capacitor can keep voltage balance through the flying capacitor C_4.

Actually, the capacitor C_4 acts as the second spiker, which is in parallel with different dc link capacitors in different switching states. So long as Group A or Group B can switch once in one period, the voltages of the capacitors can keep balance. As seen from Table 2, the switching devices of Group B or Group A are ON for one working state and OFF for the other working state. Accordingly, there exist two kinds of working states combination, shown in Table 2 and Table 3, respectively.

TABLE 2: FIRST KIND OF WORKING STATE'S COMBINATION FOR HMI-BSD

No. of working states	Output level V_o	S_1	S_2	S_3	S_4	S_5	S_6	Group A	Group B
1	$+2V_{dc}$	1	1	1	0	0	0	0	1

2	+1 V_{dc}	1	1	1	0	0	0	1	0
4	0 V_{dc}	0	1	1	1	0	0	1	0
6	-1 V_{dc}	0	0	1	1	1	0	1	0
8	-2 V_{dc}	0	0	0		1	1	1	0

TABLE 3: SECOND KIND OF WORKING STATE'S COMBINATION FOR HMI-BSD

No. of working states	Output level V_o	S_1	S_2	S_3	S_4	S_5	S_6	Group A	Group B
1	+2V_{dc}	1	1	1	0	0	0	0	1
3		0	1	1	1	0	0	0	1
5		0	0	1	1	1	0	0	1
7		0	0	0	1	1	1	0	1
8	-2 V_{dc}	0	0	0		1	1	1	0

It can be seen from Table 2 that for the first working states combination, the switching devices of Group B are turned on only when the highest output level (+2U_{dc}) appears and turned off when other four output levels appear. The pulse width modulation (PWM) carriers arrangement of this working states combination is shown in Fig.6(a). As seen from Fig.6(a), every carrier band from top down corresponds to Group B, S_1, S_2, and S_3 in turn.

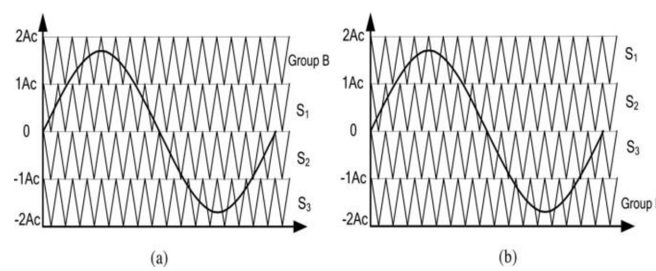

Figure 6: PWM carriers arrangement of the HMI-BSD

When the HMI-BSD operates under the condition of a lower modulation ratio (M < 0.5), the output voltages will change from five levels to three levels, i.e., the highest output level cannot be realized for the lower modulation index, and then Group B will lose the chance of being turned on and being turned off all the time. In the like manner, for the second working states combination listed in Table 3, the switching devices of Group B are turned off only when the lowest output level (-2U_{dc}) appears and turned on when other four output levels appear. The carriers arrangement of this working states combination is shown in Fig.6(b). As seen from Fig.6(b), every carrier band from top down corresponds to the switching devices of S_1, S_2, S_3, and Group B in turn. When the modulation ratio is less than 0.5, the lowest level cannot be realized, and then Group B will have no chance to be turned OFF and be turned on all the time.

The capacitor voltage balancing can be realized only when the switching devices of Group B are turned on and off alternately; otherwise, the voltage balancing in capacitors will be broken under the condition of a lower modulation ratio. So these two kinds of working states combination must be considered together to ensure the normal operation of the HMI-BSD within the wider range of modulation degree (even less than 0.5). As a result, the switching devices of Group B are turned ON over one switching period and turned off over the next switching period, and so on, that is to say, the flying capacitors are, respectively, connected in parallel with the different capacitors alternately to ensure the realization of self-voltage balancing mechanism of capacitors.

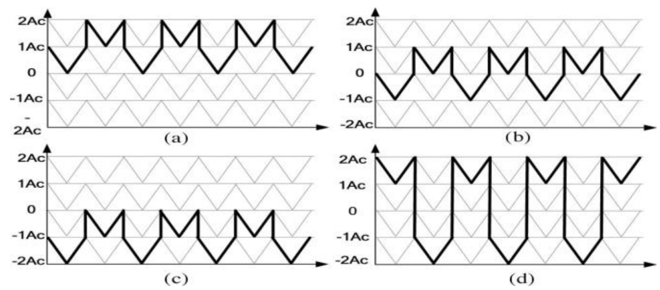

Figure 7: Carrier waveforms of the switching devices

According to the aforesaid analysis, by rearranging the carrier waveforms, the special carrier waveforms of the switching devices for the HMI-BSD are shown in Fig.7. The carrier waves for the three main switches are shown in Fig.7(a)-(c) and Fig.7(d)shows the carrier wave for switching devices of group B. By applying the special carriers in Fig.7 to the PWM method, the switching devices of Group A and Group B will be alternately turned ON or OFF by periods, thus balancing the voltages in capacitors. This balance scheme does not need complex control strategy, and is adaptive to all kinds of loads.

C. REALIZATION OF STEPPING UP THE OUTPUT VOLTAGE

Except for balancing the voltages of the capacitors, another function of the switched-capacitor part in the HMI-BSD is to step up the output voltage. Bidirectional current flows in the switched-capacitor part of the HMI-BSD, which is different from the traditional switched-capacitor circuits. With the alternate conduction of the clamping switching devices S_{c1}, S_{c6} , the voltage of each capacitor will be built up by itself and voltage values of them are identical.

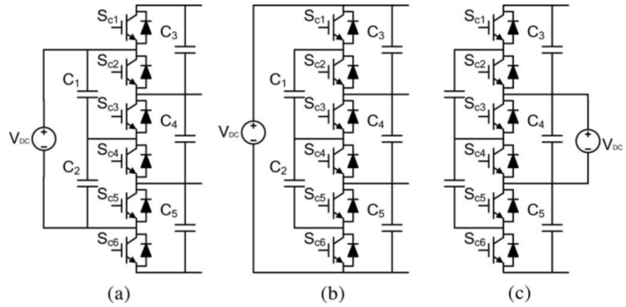

Figure 8: Three Modes of Connection of the Input DC Source.

In theory, any number of the flying capacitors or the dc link capacitors in series successively, can be connected to the terminals of the dc voltage source in the HMI-BSD. In view of the symmetry of the positive and negative output levels of the HMI-BSD, the two input terminals of the dc source should be on the output terminals symmetry, so for a single-leg five-level HMI-BSD, there are three modes of connection of the input dc source, as shown in Fig. 8.(a)-(c) The positive and negative terminals of the dc source are, respectively, connected with 1) the positive terminal of C_1 and the negative terminal of C_2; 2) the positive terminal of C_3 and the negative terminal of C_5; 3) the positive and the negative terminals of C_4.

All the capacitors sustain equal voltage $1U_{dc}$, so the peak-to-peak output voltage of a single-leg HMI-BSD is $4U_{dc}$. If the connection mode is case 1), the input dc voltage is $2U_{dc}$, only half the peak-to-peak output voltage. If the connection mode is case 2) or 3), the input dc voltage is $3U_{dc}$ or $1U_{dc}$, respectively. It is clear that the ratios of the peak-to-peak output voltage to the input dc voltage are 2, 4/3, and 4 for cases 1, 2 and 3 respectively. The peak-to-peak output voltage is equal to the dc input voltage for the conventional diode-clamped multilevel topology, while the output voltage for the HMI-BSD can be stepped up. If the HMI-BSD is in three-phase operation, the input dc source terminals should be only connected to the dc link capacitors instead of the flying capacitors because of the symmetry of the three-phase topology. And for a five-level topology, only the connection mode 1 can be used.

The function of boosting the output voltage of the HMI-BSD contributes to lessening the transformation ratio of the input transformer, thereby reducing the cost, even to eliminate the input transformer, which will benefit the design of converters in medium-high voltage application. On the other hand, compared to the conventional switched-capacitor topology, less switching devices and dc link capacitors are needed in the HMI-BSD, which can also reduce the production cost in applications.

III. SIMULATIONS AND RESULTS

The simulation of diode-clamped five level inverter had done with 600V DC input voltage and sinusoidal pulse width modulation at 0.5 modulation index. The output obtained has five steps and each step differ by a voltage of 50V. That is the five levels obtained are 0V, 50V, 100V, 150V and 200V. The switching frequency is 5kHz. Fig.9 and Fig.10 shows the output voltage and capacitor voltage of five level diode clamped inverter.

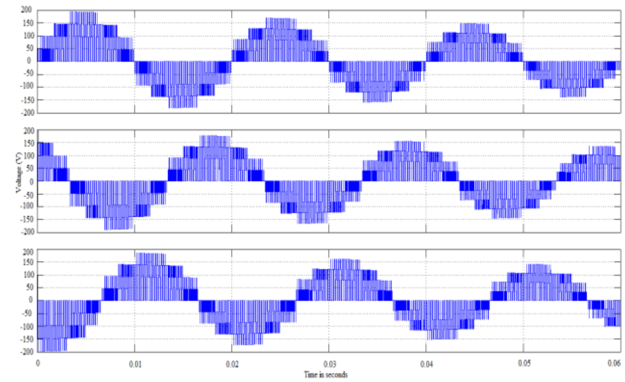

Fig. 9: Output Voltage of Five Level Diode-Clamped Inverter

From Fig.10 it can be observed that the voltage of capacitors 1, and 4 are increasing from 150V to 200V while the voltage across capacitors 2 and 3 are decreasing from 150V to 100V. From Fig.10 and Fig.9 it can be observed that the voltage across the capacitors are unbalanced due to the charging and discharging of the capacitors and the output voltage reduces according to the capacitor voltage. Hence the capacitor voltage should be balanced.

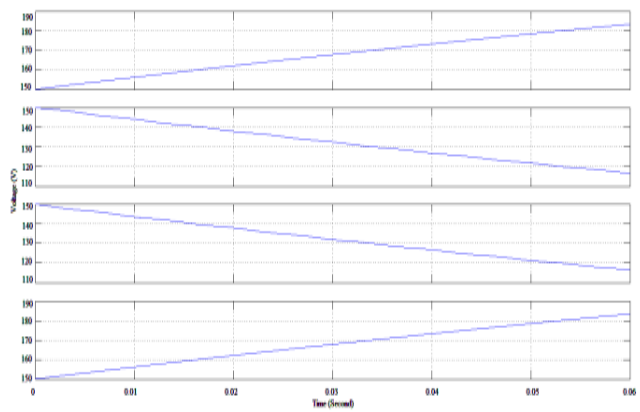

Fig. 10: Capacitor Voltage of Five Level Diode-Clamped Inverter

The simulation parameters of HMI-BSD are set as follows: the dc input voltage is 600 V; the capacitances of all capacitors are 2200 μF; the load resistance is 20Ω ; the working frequency is 1 kHz; the modulation ratio is 0.95. The input dc source terminals are connected to the positive terminal of C_1 and the negative terminal of C_2. The simulation is done for 20kHz switching frequency and as well as 1kHz switching frequency. If 1kHz switching frequency is considered, the switching losses can be reduced in practical applications. Fig.13 and Fig.14 shows the output voltage at 20kHz and 1kHz frequency respectively.

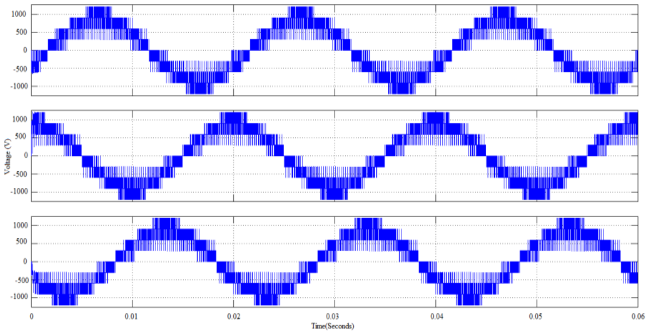

Fig.13 output voltage of HMI-BSD at20kHz

It can be observed from Fig.13 and Fig.14 that the output voltage is stepped up to 1200V with the help of switched capacitor part. The output has five levels in which each level differs by 300V. Also it can be observed from Fig.15 that the voltage across all the capacitors (both DC link capacitors and flying capacitors) are balanced and maintained at 300V.

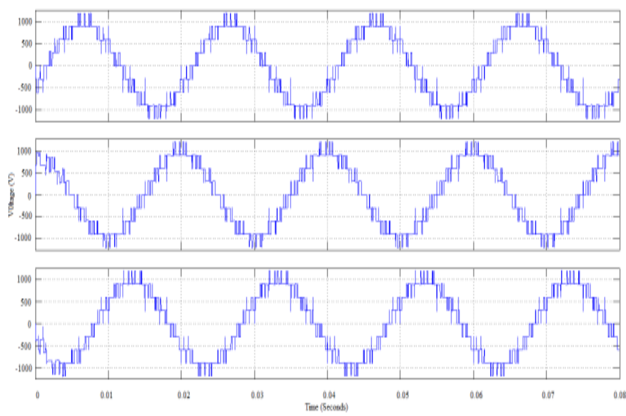

Fig.14 Output Voltage of HMI-BSD at 1kHz Switching Frequency

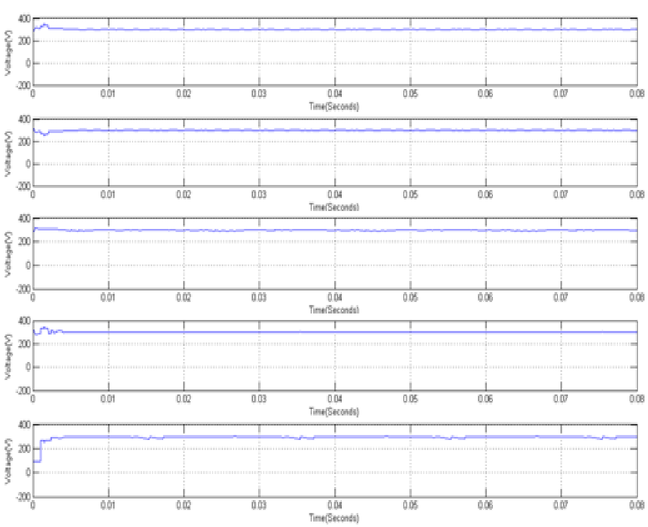

Fig.15 Capacitor Voltage of Five Level HMI-BSD

TABLE. 4 COMPONENTS REQUIR ED FOR DIFFERENT FIVE LEVEL TOPOLOGIES

Five level topology	Capaci-tors	Indu-ctors	Diodes	No. of main switching devices	No. of clamping switching devices
HMI-BSD	5	0	6	6	6
DCI	4	0	6	8	0

The components required per leg is given in Table 4. From the table it can be observed that the switching devices required for HMI-BSD is 12 while the other two topologies require 8. But with consideration of output voltage it is viable. From the results and circuit configurations it can be understand that the voltage balancing using auxiliary circuit need additional circuit and control complexity because the current and voltage has to be sensed for control purpose. But HMI-BSD has only simple control technique as well as it can reduce the transformation ratio of input transformer and balance the capacitor voltages.

VI. CONCLUSION

The structure and the principle of operation of Hybrid Multilevel Inverter Based on Switched Capacitor and Diode Clamped units are introduced. The switched-capacitor circuits are applied to balance the voltage of dc link capacitors and flying capacitors with any load conditions, as well as participate in synthesizing the output voltage levels. Both advantages of the switched-capacitor and the diode-clamped circuits are included in the HMI-BSD by the combination of the two circuits. Not only this new topology balances dc link capacitors, but also it can step up the output voltage with kinds of boosting modes, which will contribute to lessen the turns ratio of the input transformer, even to eliminate it. Compared to the other switched-capacitor topology, the less switching devices and dc link capacitors are needed in the HMI-BSD. In conclusion, the application of the switched-capacitor circuit in the HMI-BSD can reduce the cost to a certain extent. The HMI-BSD can be expanded to any n-level converter, and operate effectively under the three-phase condition. Finally, the validity of the HMI-BSD is verified by the simulation of five level HMI-BSD and compared with five level diode-clamped topology
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Author Profile

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