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COMPARATIVE ANALYSIS OF MULTILEVEL INVERTERS

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ABSTRACT

Power Electronic appliance that converts DC power into AC power at the critical voltage and frequency level is known as Inverter. Voltage Source inverters generate an output voltage or current with levels either zero to positive voltage or zero to a negative voltage that implies two levels. These bi-level inverters are powered by various types of gating signals like square, quasi - square and sinusoidal Pulse width modulated signals. Various gating signals result in various harmonic levels in the outcome signal. In this paper, a hardware model of a single-phase inverter using MOSFETs as the power switches has been developed

Inverters are used in a large number of power applications. The function of an inverter is to convert DC power to AC, This paper is focused comparison of different types of multi-level inverters. These are different based on their structure and principle of operation etc. Classification has been done based on the required output. Multilevel inverters are also classified: cascading H bridge converter, diode clamped and finally flying capacitor multilevel inverter.

INTRODUCTION

Multilevel power conversion technology is a very rapidly growing area of power electronics with a good potential for further development. The most attractive applications of this technology are in the medium voltage and high power range, and include motor drives, power distribution, power quality and power conditioning applications. Ordinary two level inverters cannot be used for high power and high voltage applications because of limitation in power handling capability and rating of the semiconductor devices. To overcome the limited semiconductor voltage and current ratings, some kind of series and/or parallel connection will be necessary thereby allowing greater working voltages to be reached, which in turn increases the power they are able to handle. Due to their ability to synthesize waveforms with a better harmonic spectrum and attain higher voltages, multi-level inverters are receiving increasing attention in the past few decades. The three most important topologies have been proposed for multilevel inverters: diode-clamped (neutral-clamped); capacitor-clamped (flying capacitors) and cascaded H-Bridge Multilevel inverter with separate dc sources.Diode clamped requires more no of diodes and flying capacitor has capacitor balancing problem. In addition, several other topologies have been proposed in the literature. It is one of the topologies proposed for drive applications which meet the requirements such as highpower rating with reduced THD and switching losses.

HISTORY AND TYPES OF INVERTERS

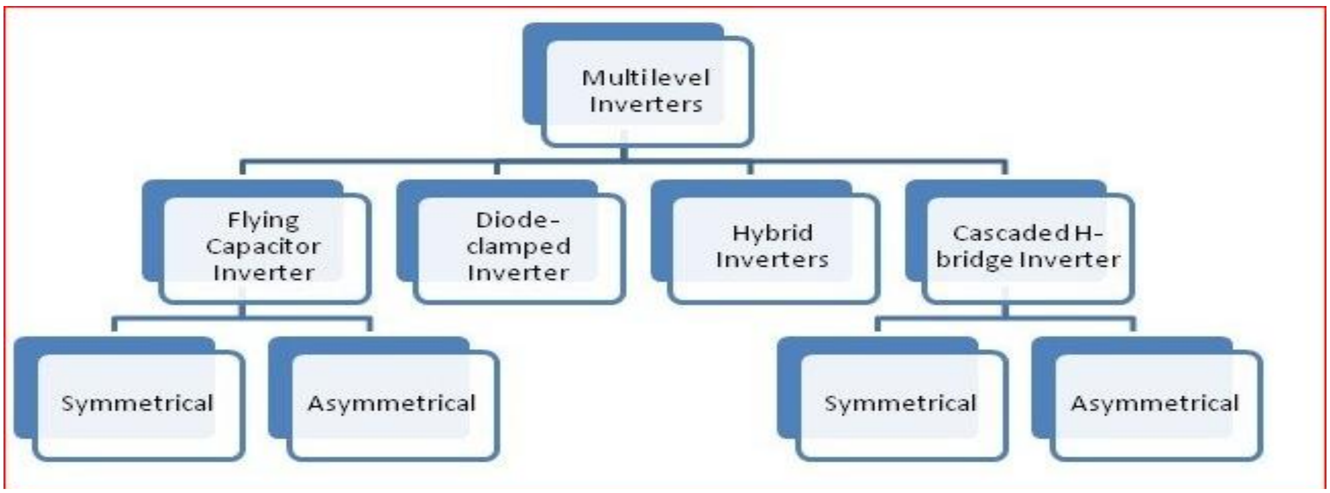

Fig 2.1

The history of multilevel inverter began in mid1970s, when the first patent describing an inverter topology capable of producing multilevel voltage from various DC voltage sources was published by Baker and Bannister (1975).It was started with three level inverter. Later developed topologies of several levels.it uses power electronic semi-conductor switch with separate dc voltage sources.Batteries and different renewable energy sources are used as the dc voltage sources. The desired voltage and power level are achieved with the combination of these structures. Power electronic inverters are widely used in industrial power conversion systems both for utility and drives applications.

2.1 TYPES OF INVERTERS:

Inverter is a power electronic device which will converts power in DC form to AC form at required frequency and voltage output.

Inverters can be classified into two major categories:

1. Voltage Source Inverter (VSI) − Voltage source inverter will have stiff DC source voltage, which means that the DC voltage will have limited or zero impedance at the inverter input terminals.

2. Current Source Inverter (CSI) − Current source inverter will be supplied with a variable current from a DC source which has high impedance and as a result of this, current waves will not be influenced by the load.

Depending upon phase these are classified into two types:

a) Single-phase inverters
b) Three-phase inverters

a) Single phase inverters

These are of two types

i) Full bridge inverter and

ii) Half bridge inverter.

i)Half Bridge Inverter

Half Bridge inverter is the basic building block of a full bridge inverter which consists of two switches and each of its capacitors will have a voltage output equal to vdc/2. Additionally, switches will be complementing each other i.e. if one is switched ON the other will go OFF.

ii) Full Bridge Inverter

Full Bridge inverter circuit used to convert DC to AC and it uses the closing and opening the switches in the right sequence for the conversion. It includes four types operating states according to the closed switches.

b) Three Phase Inverter

A three-phase inverter is used to convert the DC input into a three-phase AC output. The main three arms of three phase inverter are delayed by an angle of 120° while creating a three-phase AC supply.

2.2 TYPES OF MULTILEVEL INVERTERS:

Construction of multilevel inverter is used to create a sinusoidal ac voltage waveform from several dc voltage levels. The output voltage waveform has more steps as the voltage levels increases and a staircase voltage waveform is obtained.

There are essentially three types of multilevel inverters:

1) CascadedH-Bridge

2) Diode-Clamped

3) Flying-Capacitor

1) Cascaded H-Bridge Multilevel Inverter

Cascaded H-Bridge multilevel inverter can be used to both single phase and three phase conversions. At least three voltage levels are required for a multilevel inverter. The advantages of the cascaded inverter are: They require lesser components to obtain the output voltage levels when compared to diode clamped and flying capacitor inverters, possibility of optimized circuit design and packaging, no need of extra clamping diodes and capacitors and switching losses and stresses can be reduced with the help of soft switching techniques. The disadvantage of the cascaded inverter is that for real power transmission, they need separate dc voltage sources.

H- Bridge cell:

Each H-Bridge cell consists of four switches and four diodes, like every H-Bridge, different combinations of switch positions to determine different voltages such as positive, negative and zero voltages. Two switching combinations are present at zero voltages.

2) Diode Clamped Multilevel Inverter

The most commonly used multilevel topology is the diode clamped inverter, in which thediode is used as the clamping device to clamp the dc bus voltage so as to achieve steps in the output voltage. The neutral point converter proposed by Nabae, Takahashi, and Akagi in 1981was essentially a three-level diode-clamped inverter. Later these are developed for applications like static VAR compensation and adjustable speed. The advantages are capacitors can be pre-charged as a group and Efficiency is high for fundamental frequency switching and When the number of levels is high enough, harmonic content will be low enough to avoid the need for filters. The disadvantages are: Real power flow is difficult for a single inverter because the intermediate dc levels will tend to overcharge or discharge without precise monitoring andcontrol. The number of clamping diodes required is quadratically related to the number of levels.

3) Flying Capacitor Multilevel Inverter

The capacitor clamped inverter alternatively known as flying capacitor was proposed byMeynard and Foch in 1992. The structure of this inverter is similar to that of the diode-clamped inverter except that instead of using clamping diodes, the inverter uses capacitors in their place. The flying capacitor involves series connection of capacitor clamped switching cells. This topology has a ladder structure of dc side capacitors, where the voltage on each capacitor differs from that of the next capacitor. The voltage increment between two adjacent capacitor legs gives the size of the voltage steps in the output waveform.

Advantages: Added clamping diodes are not needed. It has switching redundancy within the phase, which can be used to balance the flying-capacitors so that only one dc source is needed and the required number of voltage levels can be achieved without the use of the transformer.

Disadvantages: Control is complicated to track the voltage levels for all of the capacitors. Pre-charging all of the capacitors to the same voltage level and startup are complex. Switching utilization and efficiency are poor for real power transmission.

CASCADED H-BRIDGE MULTILEVEL INVERTER

One more alternative for a multilevel inverter is the cascaded multilevel inverter or seriesH-bridge inverter. The series H-bridge inverter appeared in 1975. Cascaded multilevelinverter was not fully realized until two researchers, Lai and Peng. They patented it andpresented its various advantages in 1997. Since then, the CMI has been utilized in a wide range of applications. With its modularity and flexibility, the CMI shows superiority in high-power applications, especially shunt and series connected FACTS controllers. The CMI synthesizes its output nearly sinusoidal voltage waveforms by combining many isolated voltage levels. By adding more H-bridge converters, the amount of VAR can simply increased without redesign the power stage, and build-in redundancy against individual H-bridge converter failure can be realized. A series of single-phase full bridges makes up a phase for the inverter. A three-phase CMI topology is essentially composed of three identical phase legs of the series-chain of H-bridge converters, which can possibly generate different output voltage waveforms and offers the potential for AC system phase-balancing. This feature is impossible in other VSC topologies utilizing a common DC link. Since this topology consists of series power conversion cells, the voltage and power level may be easily scaled. The dc link supply for each full bridge converter is provided separately, and this is typically achieved using diode rectifiers fed from isolated secondary windings of a three-phase transformer. Phase-shifted transformers can supply the cells in medium-voltage systems in order to provide high power quality at the utility connection.

3.1 OPERATION OF CASCADED MULTILEVEL INVERTER:

The converter topology is based on the series connection of single-phase inverters with separate dc sources. Fig. 3.1 shows the power circuit for one phase leg of a three-level, five-level and seven-level cascaded inverter. The resulting phase voltage is synthesized by the addition of the voltages generated by the different cells. In a 3-level cascaded inverter each single-phase

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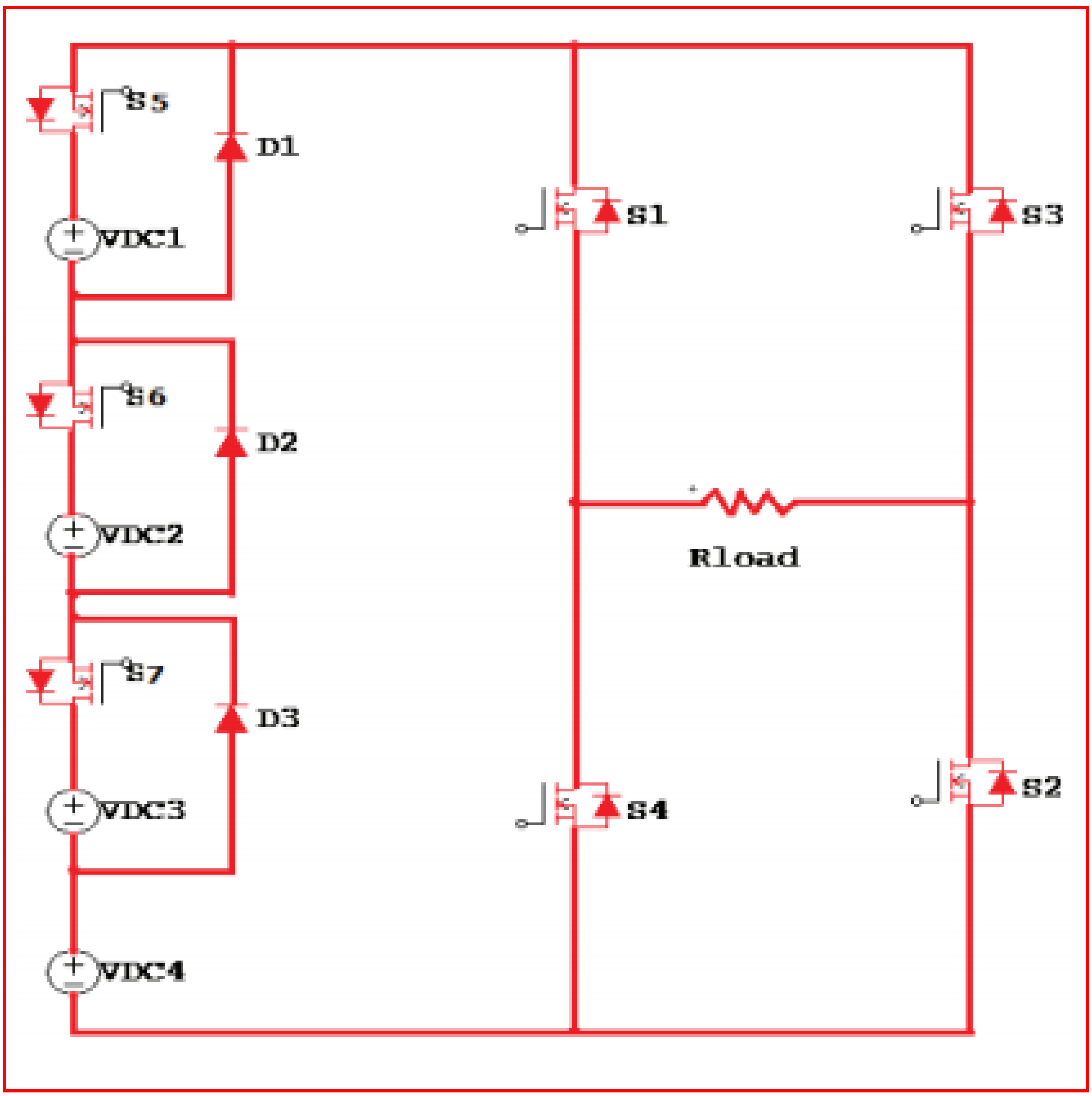
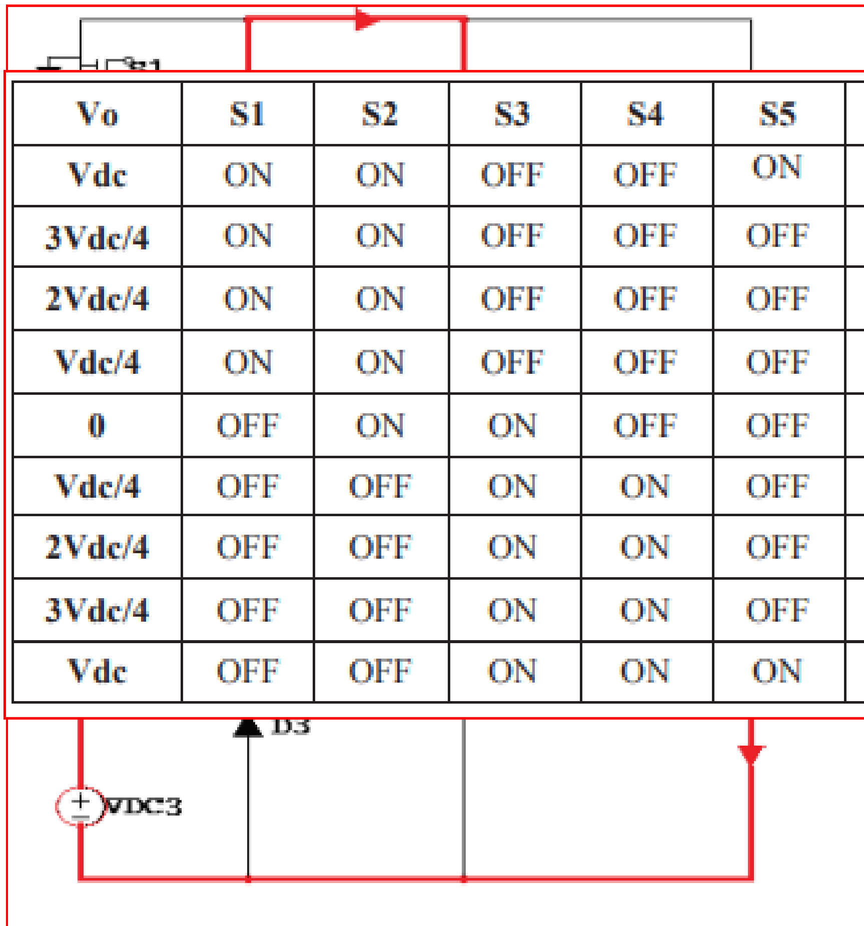
full-bridge inverter generates three voltages at the output: $+V_{DC}$, zero, $-V_{DC}$ (zero, positive dc voltage, and negative dc voltage). This is made possible by connecting the capacitors sequentially to the ac side via the power switches. The resulting output ac voltage swings from-DC to +DC with three levels, -2Vdc to +2Vdc with five-level and -3Vdc to +3Vdc with seven-level inverter. The staircase waveform is nearly sinusoidal, even without filtering.

3.2 OPERATION OF SYMMETRICAL CHBMLI:

Symmetrical Cascaded H Bridge Inverter(SCHB-MLI) topology.In this Circuit, when Misfit



Controlled Switch is Turned On, the DC Voltage Source and MOSFET Controlled Switch is connected in series, so that the current flows from DC Source to MOSFET and the Diode becomes Reverse biased Condition. When MOSFET controlled Switch is turned OFF, the Current flows via diode and the diode is forward biased.The Circuit needs four DC voltage source,7 switches and 3 diodes. The 4 DC source are equal with Voltage of 100VDC, and this circuit will generate Nine Level output voltage of 400VDC, 300VDC, 200VDC, 100VDC, 0VDC, -100VDC, -200VDC, -300VDC, -400VDC respectively.



Vo	S1	S2	S3	S4	S5	S6	S7
Vdc	ON	ON	OFF	OFF	ON	ON	ON
3Vdc/4	ON	ON	OFF	OFF	OFF	ON	ON
2Vdc/4	ON	ON	OFF	OFF	OFF	OFF	ON
Vdc/4	ON	ON	OFF	OFF	OFF	OFF	OFF
0	OFF	ON	ON	OFF	OFF	OFF	OFF
Vdc/4	OFF	OFF	ON	ON	OFF	OFF	OFF
2Vdc/4	OFF	OFF	ON	ON	OFF	OFF	ON
3Vdc/4	OFF	OFF	ON	ON	OFF	ON	ON
Vdc	OFF	OFF	ON	ON	ON	ON	ON

Fig. 5. Output Voltage level $V_{ab} = 6V_{dc}/7$to generate the Switching Sequence

Fig 3.1

Table 3.1

Fig 3.2

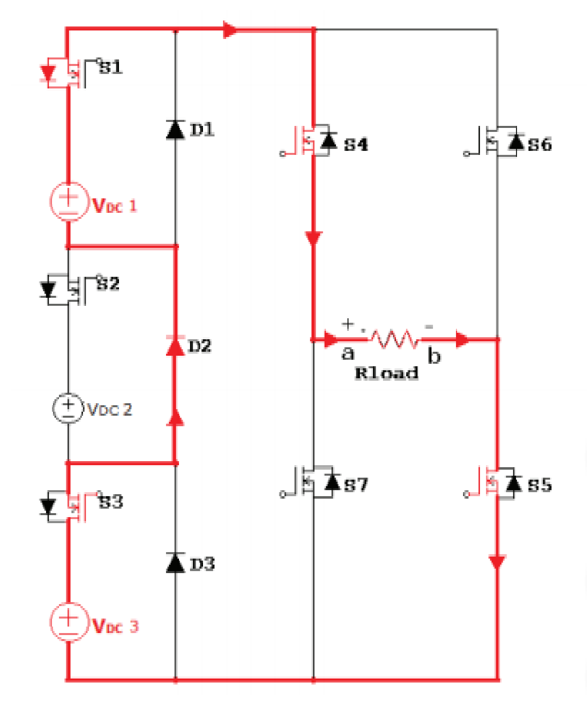


Fig. 6. Output Voltage level $V_{ab} = 5V_{dc}/7$to generate the Switching Sequence

Fig3.3

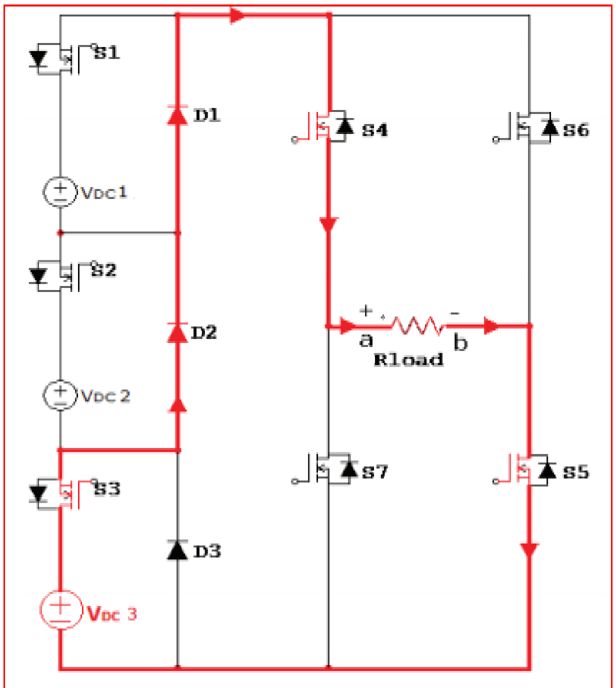


Fig. 7. Output Voltage level $V_{ab}=4V_{dc}/7$to generate the Switching Sequence

Fig 3.4

3.4 ADVANTAGES AND DISADVANTAGES OF CASCADED MULTILEVEL INVETER:

Advantages:

a) The regulation of the DC buses is simple.

b) Modularity of control can be achieved. Unlike the diode clamped and capacitor clamped inverter where the individual phase legs must be modulated by a central controller, the full-bridge inverters of a cascaded structure can be modulated separately.

c) Requires the least number of components among all multilevel converters to achieve the same number of voltage levels.

d) Soft-switching can be used in this structure to avoid bulky and lossy resistor-Capacitor-diode snubbers.

Disadvantages:

a) Communication between the full-bridges is required to achieve the synchronization of reference and the carrier waveforms.

b) Needs separate dc sources for real power conversions, and thus its applications are somewhat limited.

DIODE-CLAMPED MULTILEVEL INVERTER

The main concept of this inverter is to use diodes and provides the multiple voltage levels through the different phases to the capacitor banks which are in series. A diode transfers a limited amount of voltage, thereby reducing the stress on other electrical devices. The maximum output voltage is half of the input DC voltage. It is the main drawback of the diode clamped multilevel inverter. This problem can be solved by increasing the switches, diodes, capacitors. Due to the capacitor balancing issues, these are limited to the three levels. This type of inverters provides high efficiency because of the fundamental frequency used for all the switching devices and it is a simple method of the back to back power transfer systems

4.1 OPERATION OF DIODE-CLAMPED MULTILEVEL INVERTER:

The most commonly used multilevel topology is the diode clamped inverter, in which the diode is used as the clamping device to clamp the dc bus voltage so as to achieve steps in the output voltage. Thus, the main concept of this inverter is to use diodes to limit the power devices voltage stress. The voltage over each capacitor and each switch is V_{dc}. An n level inverter needs (n-1) voltage sources, 2(n-1) switching devices and (n-1) (n-2) diodes. By increasing the number of voltage levels the quality of the output voltage is improved and the voltage waveform becomes closer to sinusoidal waveform.

Figure.4.1 shows a three-level diode-clamped converter in which the dc bus consists of two capacitors, C_1, C_2. For dc-bus voltage V_{dc}, the voltage across each capacitor is $V_{dc}/2$ and each device voltage stress will be limited to one capacitor voltage level $V_{dc}/2$ through clamping diodes. The order of numbering of the switches for phase a is S_1, S_2, S_1 ' and S_2 '. To explain how the staircase voltage is synthesized, the neutral point n is considered as the output phase voltage reference point. If switching sequence as given in table 5.1. State condition 1 means switch ON and 0 means switch OFF.

Table 4.1

V_0	S_1	S_2	S_1'	S_2'
$V_{DC/2}$	1	1	0	0
0	0	1	1	0
$-V_{DC/2}$	0	0	1	1

There are three switch combinations to synthesize three-level voltages across a and n. Voltage level $V_{an}= V_{dc}/2$, turn on the switches S_1andS_2. Voltage level $V_{an}= 0$, turn on the switches S_2 and S_1'. Voltage level $V_{an}= - V_{dc}/2$ turn on the switches S_1',S_2'. Figure.2 (b) shows a five-level diode-clamped converter in which the dc bus consists of four capacitors, C_1, C_2, C_3, and C_4. For dc-bus voltage V_{dc}, the voltage across each capacitor is $V_{dc}/4$ and each device voltage stress will be limited to one capacitor voltage level $V_{dc}/4$ through clamping diodes. The order of numbering of the switches for phase a is S_1, S_2, S_3, S_4, S_1 ', S_2 ', S_3' and S_4 '. For example to have $V_{dc}/2$ in the output, switches S_1 to S_4 should conduct at the same time. For each voltage level four switches should conduct. As it can be seen in Table.4.1 the maximum output voltage in the output is half of the DC source. It is a drawback of the diode clamped multilevel inverter. This problem can be solved by using a two times voltage source or cascading two diode clamped multilevel inverters. The output voltage of a 5-level diode clamped multilevel inverter all of the voltage level should have the same voltage value. The switching angles should be calculated in such a way that the THD of the output voltage becomes as low as possible. The switching angle calculation method that is used in this thesis is the harmonic elimination method. In this method the lower dominant harmonics can be eliminated by choosing calculated switching angles. Table5.2 shows the output

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voltage levels and the corresponding switch states for one phase of the chosen five level DCMLI. The switches are arranged into 4 pairs (S_1, S_1'), (S_2, S_2'), (S_3, S_3'), (S_4, S_4'). If switching sequence as given in table 5.2. State condition 1 means switch ON and 0 means switch OFF.

Table 5.2

V_0	**S_1**	**S_2**	**S_3**	**S_4**	**S'_1**	**S'_2**	**S'_3**	**S'_4**
$V_{DC/2}$	1	1	1	1	0	0	0	0
$V_{DC/4}$	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0
$V_{DC/4}$	0	0	0	1	1	1	1	0
$V_{DC/2}$	0	0	0	0	1	1	1	1

The steps to synthesis the five level phase a output voltage in this work are as follows:

1. For phase a output voltage of V_{an}=0, two upper switches S_3, S_4 and two lower switches S_1 ' and S_2 ' are turned on.
2. For an output voltage of V_{an}=V_{dc}/4, three upper switches S_2, S_3, S_4 and one lower switch S_1 ' are turned on.
3. For an output voltage of V_{an}=V_{dc}/2, all upper switches S_1 through S_4 are turned on.
4. To obtain the output voltage of V_{an}= -V_{dc}/4, upper switch S_4 and three lower switches S_1 ', S_2 ' and S_3'are turned on.
5. For an output voltage of V_{an} = -V_{dc}/2, all lower switches S_1 ' through S_4 ' are turned on.

The phase a output voltage Van has five states: V_{dc}/2, V_{dc}/4, 0, - V_{dc}/4 and - V_{dc}/2.

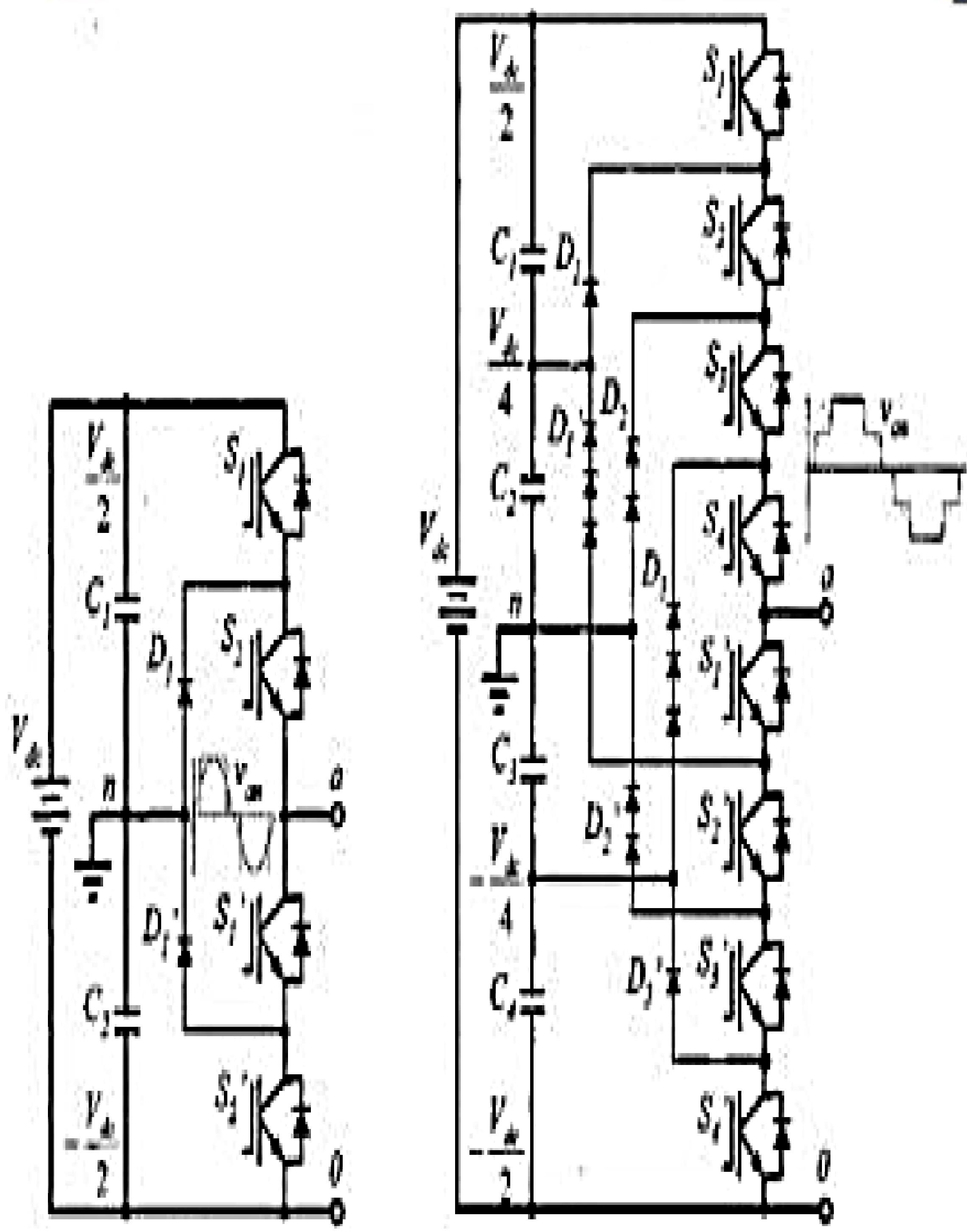

Fig 4.1

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4.2 ADVANTAGES AND DISADVANTAGES OF DIODE-CLAMPED MULTILEVEL INVERTER:

Advantages:

1. Minimum capacitance requirement of the converter due to sharing of a common bus DC voltage by all three phases. As a result this topology is suitable for high voltage back-to-back interconnections and adjustable speed drives.
2. The capacitors can be pre-charged as a group.
3. If switching is done at fundamental frequency then the efficiency of inverter is high. 4. Less number of devices is needed as compared to cascaded H-Bridge topology.
4. These inverters can be used as back to back inverters.

Disadvantages:

1. Flow of real power is difficult for single inverter as intermediate DC levels will tend to discharge and overcharge without precise monitoring and control.
2. The number of clamping diodes required is quadratically related to the number of levels, determination of which for high number of output levels can become complex.
3. System is not flexible, reconfiguration of inverter cannot be done on occurrence of fault and as a result this topology is not redundant, i.e., if any switch gets damaged, the whole inverter gets offline

CONCLUSION

PARAMETERS	CHBMLI	DCMLI	FCMLI
No. of Levels	5	5	5
Modulation Strategy	Level Shifted PWM	Level Shifted PWM	Level Shifted PWM
No. of Triangular Waves Required	8	8	8
No. of Sinusoidal Waves Required	2	2	1

Extra logic gates required	required	none	none
Current THD	15.90%	17.48%	17.82%
No. of Uncontrollable Devices Required	0	24 diodes+ 4 split capacitors	12 capacitors+4 split capacitors
No. of Voltage Sources Required	4	1	1
Output voltage	$\frac{\sqrt{5}Vs}{2}$	$\frac{\sqrt{5}Vs}{4}$	$\frac{\sqrt{5}Vs}{4}$
EX:Input voltage	200V	200V	200V
Output voltage levels	200V,100V,0,100V,200V	100V,50V,0,-50V,-100V	100V,50V,0,-50V,-100V
advantages	1.The regulation of the DC buses is simple. 2.We get same switching frequencies for all the switches. 3.Modular structure is easier to analyze 4.Requires the least number of components among all multilevel converters to achievethe same number of voltage levels.	1.Low cost and less components due to less number of capacitors. 2. Can be operated on SDCS 3. These inverters can be used as back to back inverters.	1.electromagnetic compatibility (EMC) problems can be reduced. 2.Each branch can be analyzed independently 3. Input current- Multilevel converters can draw input current with low distortion. 4.lower switching frequency usually means lower switching loss and higher efficiency.

disadvantages	1.Communication between the full-bridges is required to achieve the synchronization of reference and the carrier waveforms. 2. Needs separate dc sources for real power conversions, and thus its applications are somewhat limited.	1.For more than three levels, the charge balance gets disturbed. 2. Output voltage gets limited. 3. The number of clamping diodes required is quadratically related to the number of levels, determination of which for high number of output levels can become complex.	1.Complex start-up 2.Lower Switching efficiency 3.Capacitors are expensive than diodes 4.Voltage control across all the capacitors is difficult
Applications	PV, Fuel cells, Motor drive system, battery system	Motor drive system,STATCOM	Motor drive system,STATCOM

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