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SWITCHED CAPACITOR MULTILEVEL INVERTER WITH DIFFERENT MODULATION TECHNIQUES

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Abstract— **A multilevel inverter is a power electronic device that is used for high voltage and high power application because of its characteristics of generating a sinusoidal voltage based on several DC voltage levels. They give good quality output resulting with lower harmonic distortion in the output. This topology is designed based on switched-capacitor voltage pump technique and the number of output levels is defined by the number of switched-capacitor cells cascaded. Only one dc voltage source is needed and the problem of voltage balancing across the capacitor is avoided as well. A small input voltage can be used to generate a boosted output voltage, by switching the capacitors in parallel and in series. Number of switching devices and other components used in the circuit are reduced, compared to the conventional cascaded multilevel inverters of same configuration. This work also presents the comparative study of various Multicarrier Pulse Width Modulation techniques with Sinusoidal reference modulating signal. Performance factors such as % THD and voltage stress across the switches are measured for different modulation techniques and the results are studied. SPWM method with the different carrier based PWM such as sinusoidal PDPWM, sinusoidal PODPWM, APODPWM, VFPWM, COPWM and Sampling PWM (Symmetrical and Asymmetrical) has been analyzed. The simulations for switched capacitor seven level inverter using different modulation techniques are done with MATLAB/SIMULINK software.**

Index Terms— **Multilevel Inverter, Self-balancing, Charging, Single DC Source, Switched Capacitor**

I. INTRODUCTION

In recent years, multilevel inverters are attracting lot of attentions due to the increasing higher power quality requirements. It possesses the several features such as reduced harmonic distortion, near sinusoidal output voltage waveform and reduces dv/dt stress. Multilevel inverter produce a stepped output voltage with reduced harmonic profile compared to two level inverters. Conventionally, multilevel inverters are classified in to two categories: Type 1 and Type 2. Type 2 inverter uses multiple dc voltage capacitors; neutral point clamped [1] and flying capacitors. Type1 inverter uses multiple dc voltage sources; cascaded H-bridge inverter [2]. Type 1 inverters are again divided in to two: symmetrical and asymmetrical inverters. In cascaded symmetrical inverters all the dc voltage sources are equal where as asymmetrical inverter uses unequal voltage sources. Problem of voltage balancing among dc link and clamping capacitors exists in both neutral point clamped and flying capacitor inverters [2]. Diode clamped or neutral clamed has the difficulty of increase in the number of clamping diodes as the level increases. Similarly, in flying capacitor the number of capacitors increases and system becomes bulkier. Among these inverter topologies cascaded inverter achieves greater reliability and simplicity.

From normal inverter, magnitude of the inverter output is same as that of input voltage when the modulation index is equal to one. To offer output voltage greater than input we have to use a dc boost converter. Other method is to use inductors or transformers but at higher power transformer should withstand heavy magnetic core so that it can sustain higher power level [3]. As a solution for this charge pump technique is used with switched capacitors, which does not requires any inductors. In order to overcome the difficulties of the classical inverters, switched capacitor boost multilevel inverters are used. A switched capacitor (SC) inverter uses a charge pump technique using switched capacitors. And higher output voltage generation is by switching the capacitors in series and parallel [3] [4]. This inverter topology is connecting a switched capacitor network and a full bridge inverter. Switched capacitor network consists of several parallel connected switched capacitor cells. Number of switched capacitor cell determined by the levels required [3] [4] [5]. This inverter does not require inductors make the system smaller.

Multilevel inverters are mainly controlled by sinusoidal PWM technique and the harmonic contents can be reduced by using various multicarrier PWM techniques [6]. The multicarrier pulse width modulation strategy enhances the fundamental voltage and reduces harmonic distortion of the inverter output. The power quality improvement is achieved by reducing the harmonics present in the output voltage of the inverter. There are two PWM methods mainly used in multilevel inverter control strategy [7]. One is fundamental switching frequency and another one is high switching frequency. The high switching frequency strategy is classified as space vector PWM, Selective Harmonic Elimination PWM and SPWM. Among these PWM methods SPWM is mostly used for the multilevel inverter, because it is very simple and easy to implement. In this paper, SPWM method with the

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different carrier based PWM such as PDPWM, PODPWM, APODPWM, VFPWM, COPWM and Sampling PWM has been analyzed [6] [7].

II. Switched Capacitor Boost Seven Level Inverter

A novel multilevel inverter topology connecting a multilevel DC-DC converter and a full bridge is presented. With the proposed topology, only one DC voltage source is required and many other problems such as voltage balancing, numerous active switches and complex gate driver circuits are avoided as well. The DC-DC conversion section is the key point of the whole topology, which is designed by connecting multiple SC cells. Each SC cell consists of a capacitor, two active switches and one diode. Consequently, the output voltage levels of the proposed inverter could be varied flexibly by employing different number of SC cells [8].

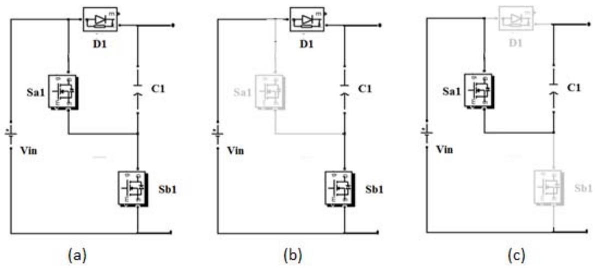

Fig 1: Switched Capacitor Cell

A new boost switched-capacitor (SC) multilevel inverter is formed by cascading two structures: a switched capacitor circuit and a two level (full bridge) inverter. A switched capacitor circuit is a combination of capacitors, switching devices such as MOSFET, IGBT, BJT etc. Figure 1(a) shows basic circuit of the SC cell. This circuit is named by basic unit and contains one DC power supply, one capacitor, two active power switches and one passive power diode. Photovoltaic (PV) cells, batteries and fuel cells can be used as a power supply in this structure. Figure 1 (b) and 1(c) show that how to carry out the charging and discharging operations for capacitor C. As it can be inspected, when the switch S_{a1} becomes OFF and S_{b1} is ON , the capacitor C1 is charged to input V_{dc} and when the switch S_{a1} turns ON and Switch S_{b1} is turned OFF, the diode becomes reverse biased and capacitor is discharged. In this mode, the power supply energy and stored energy of C are transferred to the output. It is obvious that, basic unit does not need any extra charge balancing control circuits and complicated commutation methods which is counted as a great merit of this structure [4]. Also, it is remarkable that, the internal resistance of power diode and capacitor can damp the unequal voltage between capacitor and DC voltage source during the charging operation which leads to introduce an effective and practical power circuit.

Figure 2 shows circuit configuration of the converter. In order to charge all of the capacitors and generate output voltage waveform, the switches, and are driven by series/parallel conversion or combination of them. The proposed inverter structure is simpler than the conventional multilevel inverter. The above inverter does not have any inductors which make the system large. Capacitors, batteries, and other DC voltage sources can be used as the voltage sources for the inverter. Therefore the given multilevel inverter can be applied to grid connected photovoltaic systems etc., while maintaining these advantages.

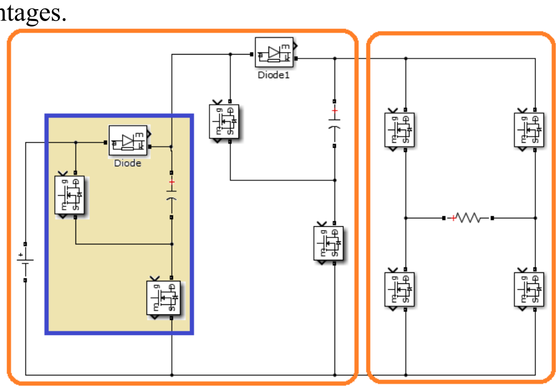

Fig 2: Seven Level Switched Capacitor Inverter

A Switched Capacitor (SC) circuit is used in order to obtain a boost multilevel DC voltage waveform, which is inserted between the source and the full bridge inverter [8]. The multilevel dc output voltage of the switched capacitor circuit is the input voltage of the classical full bridge inverter, resulting in a staircase output voltage waveform. The multilevel output voltage that is obtained is larger voltage than the input voltage by switching the capacitors in series and in parallel. Such a multilevel waveform is close to a sinusoidal, its harmonic content can be reduced when compared to the conventional multilevel inverter by using the PWM control strategy. Both the boost SC active switch and the inverter power switches are operated with a high switching frequency in order to obtain a multilevel output voltage waveform.

a. Modes Of Operation

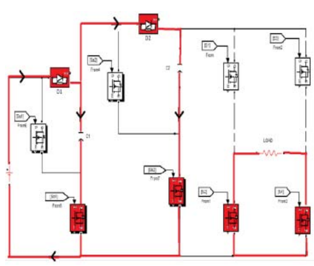

Fig 3: Mode 1(Zero voltage)

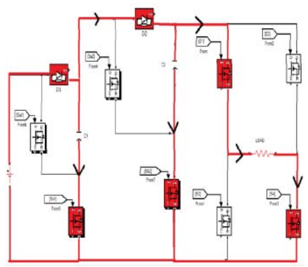

Fig 4: Mode 2($V_o = V_{dc}$)

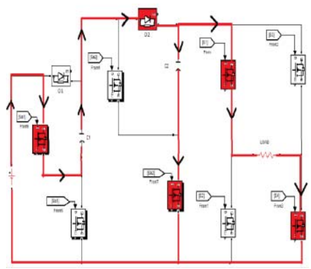

Fig 5: Mode 3 ($V_o = 2V_{dc}$)

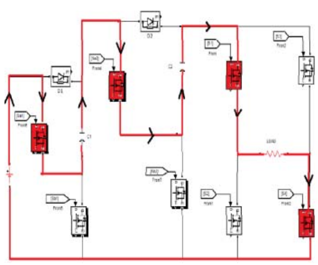

Fig 6: Mode 4 ($V_o = 3V_{dc}$)

The inverter outputs a multilevel AC voltage which is larger than the input DC voltage by means of switching the capacitors in series and in parallel. When the capacitor and the input voltage source are connected in parallel, the capacitors are charged as shown in Figure 3. When the capacitor and input voltage source are connected in series, the capacitors are discharged as shown in Figure 5 and 6. The operation of the 7-level inverter can be explained using 3 states via; the state when all the capacitors are connected in parallel, the state when some of the capacitors are connected in series, and the state when all the capacitors are connected in series. The basic operations of the inverter are used to obtain a positive and negative cycle for the multilevel output. The positive half cycle is obtained with switches S1 and S4 of full bridge inverter ON and negative half cycle with switches S2 and S3 of inverter ON.

III. CONTROL STRATEGY

To control and to generate high quality output waveform, an appropriate modulation scheme is required. Among the various modulation schemes, an important family of modulation technique, multicarrier pulse width modulation stands out because it offers significant simplicity and easy to implement switching waveforms. Carrier modulation techniques are classifieds into two types: based on type of carriers and type of modulating signals.

TYPES OF CARRIER SIGNALS

In this section, simplified way to generate different type of carrier signals are illustrated based on level shifted such as Phase Disposition, Phase Opposition Disposition, Alternate Phase Opposition Disposition and Carrier Overlapping [14][15].

A. Sinusoidal Multicarrier PWM

For an m-level inverter (m-1) carriers with same frequency f_c and same peak-to-peak amplitude Ac are used. The reference waveform has amplitude Am and frequency fm and placed at zero reference. The reference wave is continuously compared with each of the carrier signals. If the reference wave is more than a carrier signal, then the active devices corresponding to that carrier are switched ON. Otherwise, the device switched OFF.

1. **Sinusoidal Phase Disposition PWM**

In phase disposition method all the carriers are in phase with each other as shown in Figure 7. This method uses six carrier signals to generate seven level output voltage. It is based on the comparison of a sinusoidal reference waveform with vertically shifted carrier waveform.

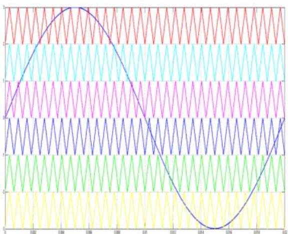

Fig 7: Sinusoidal PD PWM

2. **Sinusoidal Phase Opposition Disposition PWM**

The carrier signals above the zero axis have same frequency, same amplitude and in phase with each other. But the below the zero axis all the carrier wave have same frequency, same amplitude and in phase but all carrier waves are phase shifted by 180 degree compare to the above zero axis carrier waveform [6] [7].

3. **Alternative Phase Opposition Disposition PWM**

All the carrier waveforms have same frequency and same amplitude, but every carrier is phase shifted 180 degrees from its neighbour. Odd carrier waveforms are in phase but compare to even carrier waves they are out of phase with 180 degree.

4. **Variable Frequency PWM**

The Principle of VFPWM technique is to use the several carriers of different frequencies with single modulating waveform. In this all the carriers are in phase and the carriers are disposed so that the bands they occupy are contiguous.

5. **Carrier Overlapping PWM**

In the carrier overlapping technique, 6 carriers are disposed such that the bands they occupy overlap each other, the overlapping vertical distance between each carrier is Ac/2 (Ac=1). The performance of this method depends on the overlapping of the carrier signals.

B. Sampling Multicarrier PWM

The Principle of this PWM technique is to use the several carriers with sampled version of sinusoidal modulating waveform. 6 triangular carrier waveforms are compared with one sampled sinusoidal reference waveform.

1. **Symmetrical Sampling PWM**

Sampled version of modulating signal is compared with each carrier, where sampling is carried out at the instant of positive peak of the carrier as shown in Figure 8.

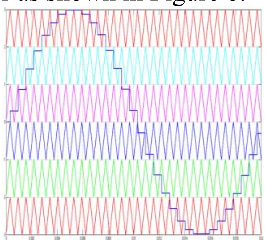

Fig 8: Symmetrical PWM

2. **Asymmetrical Sampling PWM**

Sampled version of modulating signal is compared with each carrier, where sampling is carried out at the instant of both positive and negative peak of carrier.

TYPE OF MODULATING SIGNALS

The modulating/reference wave of multilevel carrier based PWM strategies can be Sinusoidal, Third Harmonic Injected PWM, 60˚ Modulated Sinusoidal PWM and Trapezoidal PWM As far as the particular reference wave is concerned, there is also multiple schemes including frequency, amplitude and phase angle. This work focuses on multicarrier based Sinusoidal PWM Strategies which have been used in chosen Multilevel Inverter [14][15][16].

IV. SIMULINK MODEL OF PULSE GENERATION

The simulation is performed to analyze and compare the harmonic characteristics for the multicarrier PWM techniques from the view point of THD. Here six carriers are compared using the relational operators (>= and <=). Switching pulses are generated from the output of each relational operator. Pulse generation for the Sampling PWM technique such as Symmetrical and Asymmetrical sampling are simulated similar to the above method. Sample and hold element in Simulink Library is used to take the samples of the sinusoidal modulating signal. Sampling is carried out either at only positive peak or at both the positive and negative peak of the triangular carriers.

Outputs of the six relational operators are used for the seven switching pulse generation by applying proper logical operations ie, some logical functions (AND, OR, NOT) are applied on these comparison pulses to generate seven switching pulses shown in Figure 9.

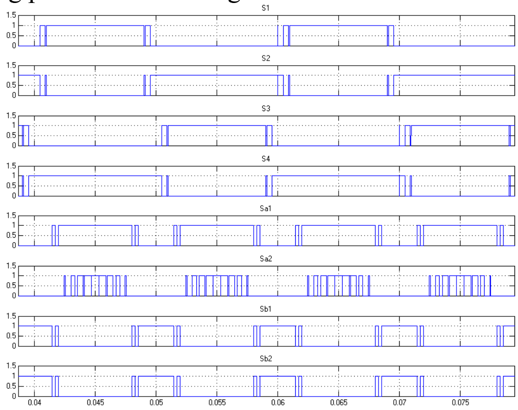

Fig 9: Switching Pulses for Seven Level Inverter

V. SIMULINK MODEL AND RESULTS

For an input of 5V, switching frequency f = 1.6 kHz and reference frequency = 50Hz, the multilevel inverter was simulated in Matlab Ra2014a. The capacitance C_k can be determined properly with considering the voltage ripple of the capacitors C_k. The capacitance C_k are calculated when the maximum voltage ripple is supposed to be 10% of the maximum voltages of the capacitors. The capacitors Ck are charged when they are connected in parallel and are discharged when they are connected in series. The capacitor of 143µF was used for 10% of maximum input voltage as voltage ripple. Figure 10 shows the Simulink model of the Switched Capacitor multilevel inverter. Subsystem in the given Simulink model is the control signal generation part.

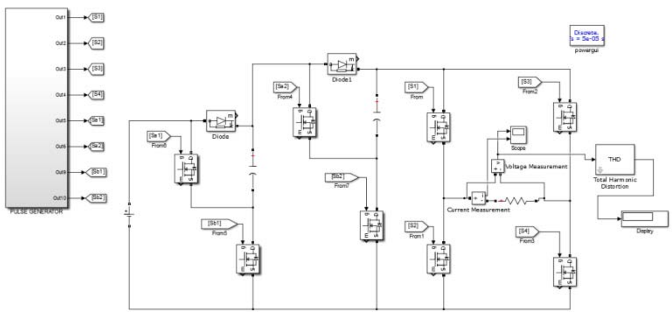

Fig 10: Simulink Model of Seven Levels Inverter

Table 1: Simulation Parameters

PARAMETERS	VALUE
Input voltage	5V
Switching frequency	1.6 KHz
Modulating frequency	50Hz
Capacitance C_1 C_2	143µF
Load Resistance	100 ohm

Table 1 describes the simulation parameters for the proposed multilevel inverter. Simulation of new Switched Capacitor Multilevel Inverter is carried out using an input of 5V; switching frequency f_c of 1.6 kHz and reference frequency f_s of 50Hz, the multilevel inverter was simulated in Matlab 2014. Resistance of 100 ohm is used here as load and the voltage and current measured across this resistor.

a. Design of Capacitors

The capacitor to be used should be such that it should retain the input voltage at the source. Use of large capacitance will cause large amount of current to be drawn from the input source as a result over current protective circuits must be added to each switches in the circuit. Figure 11 shows the voltage across the capacitor.

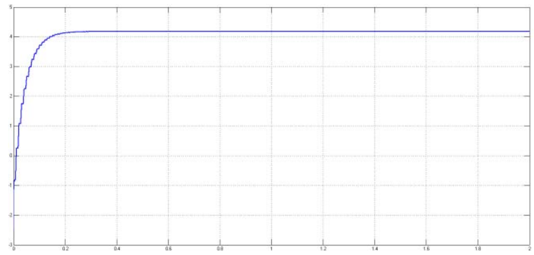

Fig 11: Capacitor Voltage

Both the capacitor charges to a voltage□ equal to the input voltage minus the voltage drop across the diode when the diode gets forward biased.

Figure 12 shows the seven level output voltage for an input of 5V, switching frequency f_c of 1.6 kHz and reference frequency f_s of 50Hz. Resistance of 100 ohm is used here as load and the voltage and current measured across these resistor. Output voltage contains seven levels and the highest level voltage is almost 13V. Here output voltage is shown using the APOD PWM technique.

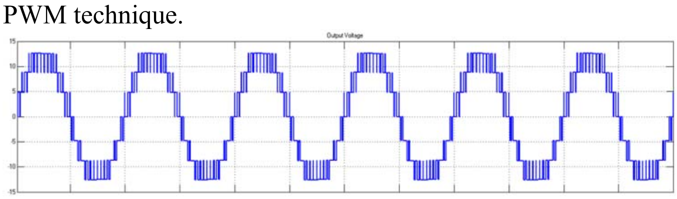

Fig 12: Seven Level Inverter Output Voltage

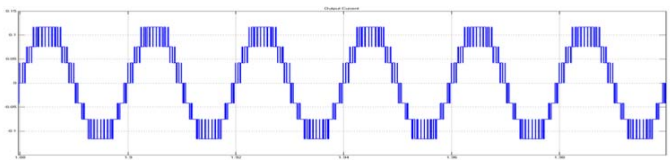

Fig 13: Seven Level Inverter Output Current

b. Voltage Stress across the switches

Figure 13 shows the Output Current of the proposed Switched Capacitor Multilevel Inverter. Waveform also contains seven level in the one half cycle. Maximum current amplitude is 0.13amps for 100 ohm load. For more number of levels connect some more SC cells in parallel at the input side of full bridge inverter.

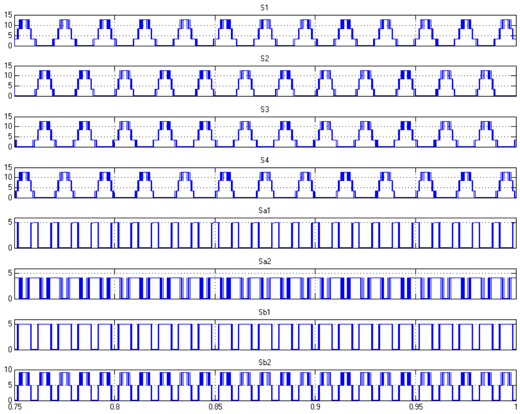

Fig 14: Voltage Stress across Switches

Figure 14 shows the voltage stress across the seven switches of the proposed Switched Capacitor Seven Level Inverter. Upper four switches belong to the full bridge inverter (S1, S2, S3 and S4). Stress across these switches almost equals to the maximum output voltage level ie, 10 volts. But less than 5 volts (input DC voltage) is drops across the Switches S_{a1} and S_{a2}. Voltage stress across the switch S_{b1} and S_{b2} is more than input but less than maximum output value.

c. Discussion

Table 2 shows the comparative study between the above mentioned PWM Techniques. From the table it is clear that all the methods give less distortion values. But the harmonic distortion from the Alternative Phase Opposition Disposition PWM Technique (APOD) is much less compared to the other PWM methods. From the other seven level inverter configurations this circuit gives better results in terms of device count and output distortion.

Table 2: Comparative Study on THD Spectrum

Modulation Scheme	**THD (%)**
Phase Disposition PWM	19.03
Phase Opposition Disposition PWM	19.20
Alternative Phase Opposition Disposition PWM	18.56
Carrier Overlapping PWM	21.86
Variable Frequency PWM	19.57
Symmetrical Sampling PWM	20.21
Asymmetrical Sampling PWM	19.15

VI. CONCLUSIONS

In this work, a boosted switched-capacitor multilevel inverter is proposed, which is combination of a DC-DC converter and a full bridge inverter. By connecting different number of Switched Capacitor cells, the output level could be varied flexibly. Also various PWM techniques for chosen for Switched Capacitor seven level inverter have been developed. It enables the simple structure and low cost of the gate driver circuits. Also this new boosted multilevel inverter using various multi carriers PWM techniques are also proposed. The open loop simulation of proposed switched capacitor multilevel inverter is performed using different multicarrier PWM techniques such as sinusoidal PDPWM, sinusoidal PODPWM, APODPWM, VFPWM, COPWM; Sampling PWM (Symmetrical and Asymmetrical) has been analyzed. The proposed multilevel inverter uses the less number of switching devices. By switching the capacitors in parallel and in series, the maximum output voltage level becomes larger than the input voltage. The inverter does not need any transformer, inductor and boost converter, so that the structure of the inverter can be simpler and smaller than the conventional two-stage inverter. The simulation results show that the total harmonic distortion (THD) in the output voltage of the proposed inverter is reduced than that of the conventional multilevel inverter. From the discussion APOD PWM shows minimum THD compared to other methods.

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