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Harmonic elimination in cascade multicell inverter using Novel SWPWM, SPWM and ISPWM: a comparison

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ABSTRACT

Multilevel inverters have become more popular over the years in electric high power application with the promise of less disturbances and the possibility to function at lower switching frequencies than ordinary two-level inverters. Multilevel inverters has been introduced as static high-power inverters for medium to high voltage applications such as large electric drives, reactive power compensations, dynamic voltage restorers and FACTS devices. Different Pulse Width Modulation (PWM) strategies have been used in multilevel inverter topologies. In this paper novel method Square Wave Pulse Width Modulation (SWPWM), Inverted Sinusoidal Pulse width modulation (ISPWM) and Sinusoidal Pulse Width modulation (SPWM) in order to minimize the Total Harmonic Distortion (THD) are used for a nine-level Cascade H-Bridge Multicell Inverter (CHMCI). The MATLAB/Simulink software program is used to verify the effectiveness of each above strategies.

Keywords - Level Shifted Modulation, Cascade H-Bridge Multicell Inverter, Total Harmonic Distortion, Pulse Width Modulation (PWM), Sinusoidal Pulse Width Modulation (SPWM), Square wave Pulse Width Modulation (SWPWM), Inverted Sinusoidal Pulse Width Modulation (ISPWM), CSF Modulation

I. INTRODUCTION

The first multilevel converter can be attributed to R. H. Baker and L. H. Bannister, who patented the cascade H-bridge with diodes blocking the source in 1975 [1]. This was followed by the Diode-Clamped Inverter [2-4] which utilizes a series capacitors bank to divide the DC bus voltage. The Flying-Capacitor [5] (FC) topology followed diode-clamped after few years.

Using these inverters allows a reduction in the size of the filtering elements. This affects the dynamic response of the inverter. Multilevel inverter is a suitable configuration to achieve high power rating and high quality output waveform and reduce switching losses which can make amends Electro-Magnetic Interference (EMI) problem besides of reasonable dynamic response [6].

In recent years several multilevel PWM methods have been proposed [7], [8]. In this paper 3 type of Level Shifted PWMs method are compared. The LS-PWM methods are compared in this paper is:

1. Sinusoidal Pulse Width Modulation (SPWM)
2. Square wave Pulse Width Modulation (SWPWM)
3. Inverted Sinusoidal Pulse Width Modulation (ISPWM)

The Difference between three above-mentioned methods is in carrier wave. In SPWM a sinusoidal reference signal is compared to a triangular waveform to generate switching signals of inverter. In SWPWM the carriers are square wave and in ISPWM the carriers are sinusoidal waveform.

In this paper, constant switching frequency and variable switching frequency techniques are discussed. The above methodologies divided into two techniques like subharmonic pulse width modulation which minimises total harmonic distortion and switching frequency optimal pulse width modulation which enhances the output voltages [9].

II. CASCADE H-BRIDGE INVERTER

A three-phase structure of a nine-level cascaded inverter is showed in Figure 1. The multilevel inverter using cascaded-inverter with separate dc sources (SDCSs) synthesizes a desired voltage from several independent sources of dc voltages, which may be obtained from batteries, solar cells or fuel cells.

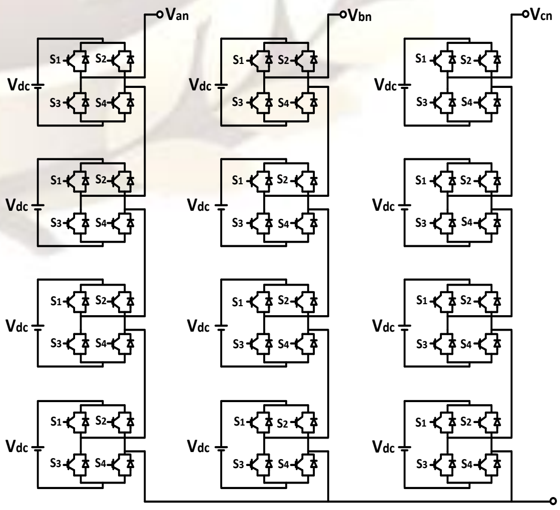


Figure 1. A three-phase structure of a nine-level cascaded inverter

This configuration recently becomes very popular in ac power supply and adjustable speed drive applications. The output of each cell will have three levels, 0 and by connecting the dc source to the ac output by different combinations of the four switches S1, S2, S3 and S4. To obtain, switches S1 and S4 are turned on, whereas can be obtained by turning on switches S2 and S3. By turning on S1 and S2 or S3 and S4, the output voltage is 0. The output voltage is the sum of the voltage that is generated by each cell. The number of output voltage levels are (2n+1), where n is the number of cells.

An example phase voltage waveform for a nine-level cascaded H-bridge inverter with four dc sources is shown in Figure 2.

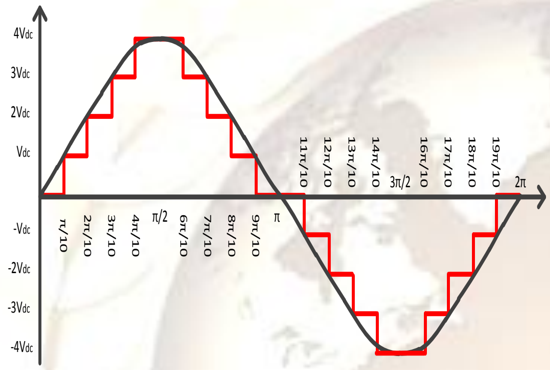


Figure 2. Line- Neutral Voltage Waveforms Nine Level CMCI

The output voltage of a cascaded H-bridge inverter leg is obtained by adding the single H-bridge output voltages as follows:

$$V_o(t) = \sum_{j=1}^{n} V_{O_j}(t) \quad (1)$$

Table 2 shows the component requirements for the Cascade H-Bridge for a three-phase setup.

Table 1. Component Requirements for the Cascade multicell inverter for a three-phase

Isolated sources	$6(\frac{m-1}{2})$
Main diodes	$6(m-1)$
Main switches	$6(m-1)$
Clamping diodes	0
Clamping capacitor	0
Smoothing ind.	0
Transformers	0

The main advantages and disadvantages of multilevel cascade h-bridge are as follows:

Advantages:

- Requires a low number of components per level
- Modularized structure without clamping components
- Possibility to implement soft-switching
- Simple voltage balancing modulation

Disadvantages:

- Needs separate isolated DC sources for real power transfer
- No common DC-bus

III. MODULATION TECHNIQUE

There are several ways to classify modulation techniques; in [7] and [8] two possible ways are presented. Here, the way shown in [8] is adopted and graphically presented in Figure 2.1. As shown in figure 3, according to switching frequency, multilevel inverter modulations are basically classified in two groups of methods: Modulation with fundamental switching frequency and high switching frequency PWM.

Fundamental switching frequency modulations produce switch commutations at output fundamental frequency and can be aimed to cancel some particular low frequency harmonic. In this class there are Space Vector Control (SVC) and selective harmonic elimination.

High switching frequency modulations are the adaptation of standard PWM to multilevels and they are meant to switch at very high frequency, about 10 to 20 kHz. Among them, there are Space Vector PWM (SVPWM), Selective Harmonic Elimination PWM (SHPWM), Phase Shifted PWM (PSPWM) and a subclass called level shifted PWM. Phase Opposition (PO), Phase Opposition Disposition (POD) and Alternate Phase Opposition Disposition (APOD) modulations belong to this last level.

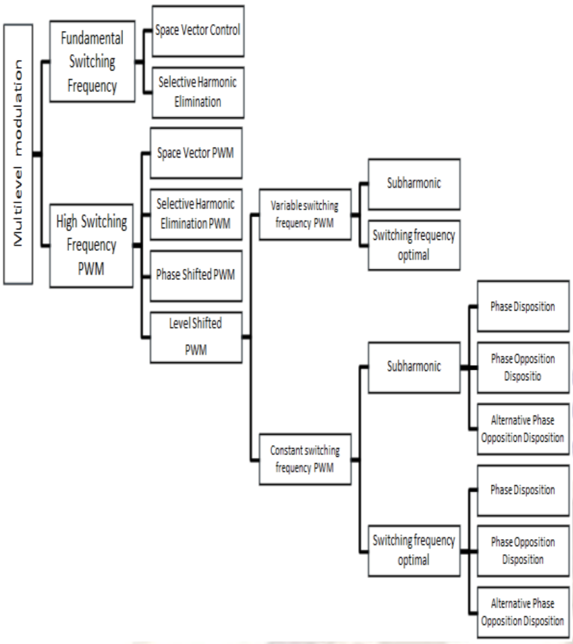
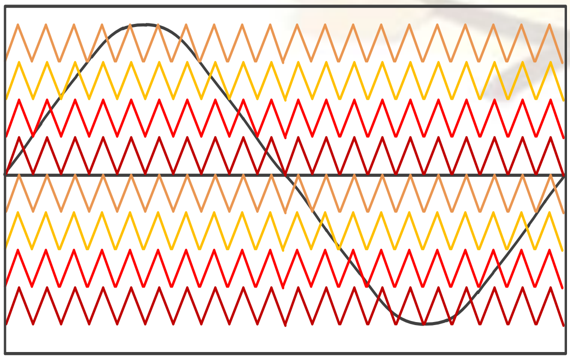


Figure 3. the Classification of PWM Multilevel Inverter Modulation Strategies

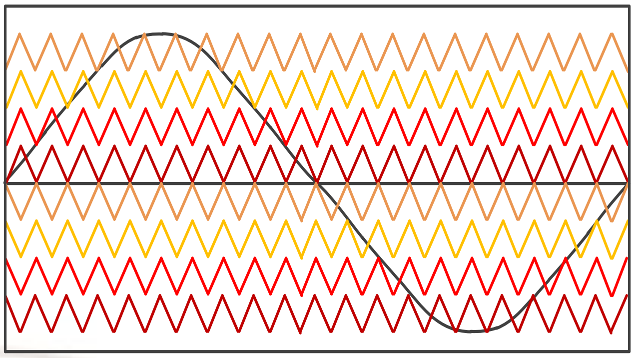
In this paper, the authors focused on the level shifted PWM strategies. Level Shifted PWMs [10-12] use more carriers, with the same amplitude and frequency, but translated in level as pictures in Figure 4 show for a 9-level converter. The number of carriers needed to generate the driving signals for a n-level converter is n-1. Level shift based on switching frequency is divided two general categories: fixed switching frequency, variable switching frequency.

There are three major kinds of LSPWMs depending on how the carriers are disposed:

- Phase Disposition (PD), where all the carriers are in phase. figure 4(a)
- Phase Opposition Disposition Square (POD), where all the carriers above the zero value reference are in phase among them, but in opposition with those below. figure 4(b)
- Alternative Phase Opposition Disposition (APOD), where each carrier band is shifted by from the nearby bands. figure 4(c)



(a)



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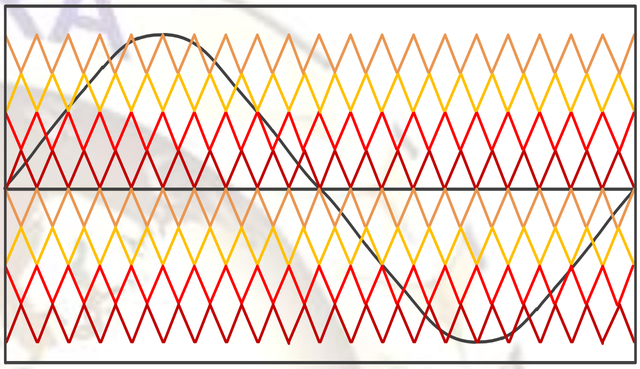
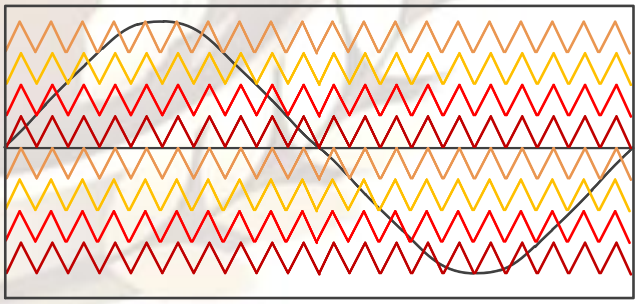


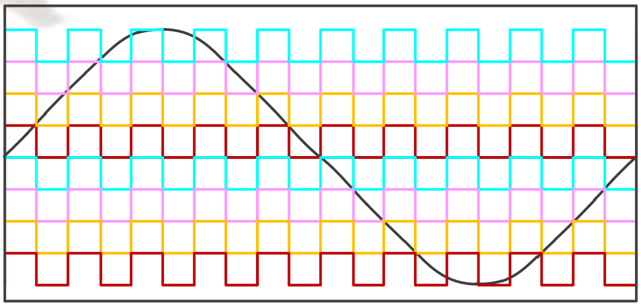
(c)

Figure 4. (a)PD-SH-SPWM, (b) POD-SH-SPWM, (c) APOD-SH- SPWM

In this paper, a level shifted PWM technique with three different carriers has been discussed in order to compare the THD of output voltage in a nine level CHMCI. The waves that used for carriers are: 1- Triangular wave (SPWM) 2- Square wave (SWPWM) 3- Sinusoidal wave (ISPWM).



(a)



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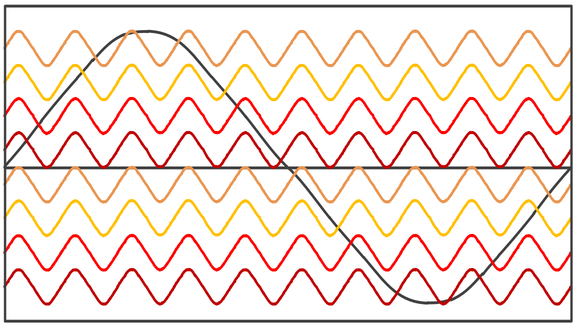


(c)
Figure 5. (a) SPWM, (b) SWPWM, (c) ISPWM

IV. CONSTANT SWITCHING FREQUENCY PWM

A- Sub-harmonic PWM

Carrara extended SH-PWM to multiple levels as follows [13]: The constant switching frequency pulse-width modulation technique is most popular and very simple switching schemes. For m-level inverter, $m-1$ carriers with the same frequency f_c and the same amplitude A_c are disposed such that the bands they occupy are contiguous. The reference waveform has peak-to-peak amplitude A_m, the frequency f_m and it is zero centered in the middle of the carrier set. The reference is incessantly compared with each of the carrier signals. If the reference is greater than a carrier signal, then the active device conforming to that carrier is switched on and if the reference is less than a carrier signal, then the active device conforming to that carrier is switched off.

The frequency modulation index m_f, which is the ratio of carrier frequency to modulating signal frequency, is expressed by equation:

$$m_f = \frac{f_c}{f_m} \qquad (2)$$

In multilevel inverters, the amplitude modulation index m_a defined as:

$$m_a = \frac{A_m}{(m-1)A_c} \qquad (3)$$

The advantages of this method are as follows:

- It has lower THD.
- It is easily applied to any multilevel inverter.
- Increase the output voltage amplitude.

The SH-PWM method has serious disadvantages such as:

- lower fundamental component
- lower voltage modulation index

In multilevel case, Sub-Harmonic PWM (SHPWM) techniques with three different disposed carrier [14], [15], have been proposed as follows:

- Phase Disposition Pulse-Width Modulation (PD-PWM), where all the carriers are in phase.
- Phase Opposition Disposition Pulse-Width Modulation (POD-PWM), where all the carriers above the zero value reference are in phase among them, but in opposition with those below.
- Alternative Phase Opposition Disposition Pulse Width Modulation (APOD-PWM), where each carrier band is shifted by 180° from the nearby bands.

PD-SH-SPWM, POD-SH-SPWM and APOD-SH-SPWM technique respectively show in figure 4a, figure 4b and figure 4c.

B- Switching Frequency Optimal PWM

This method has been presented by Menzies [16]. Triples harmonic voltage is added to refrence waveforms in the Switching Frequency Optimal Pulse-Width Modulation (SFO-PWM) method. This method consists of the instantaneous average of the minimum and maximum of the three reference voltages (Va,Vb,Vc) and subtracts this value from each of the unique reference voltages to obtain the modulation waveforms.

$$V_{offset} = \left\{ \frac{\max(V_a, V_b, V_c) + \min(V_a, V_b, V_c)}{2} \right\} \qquad (4)$$

$$V_{bSFO} = V_b - V_{offset}$$

$$V_{aSFO} = V_a - V_{offset} \qquad (5)$$

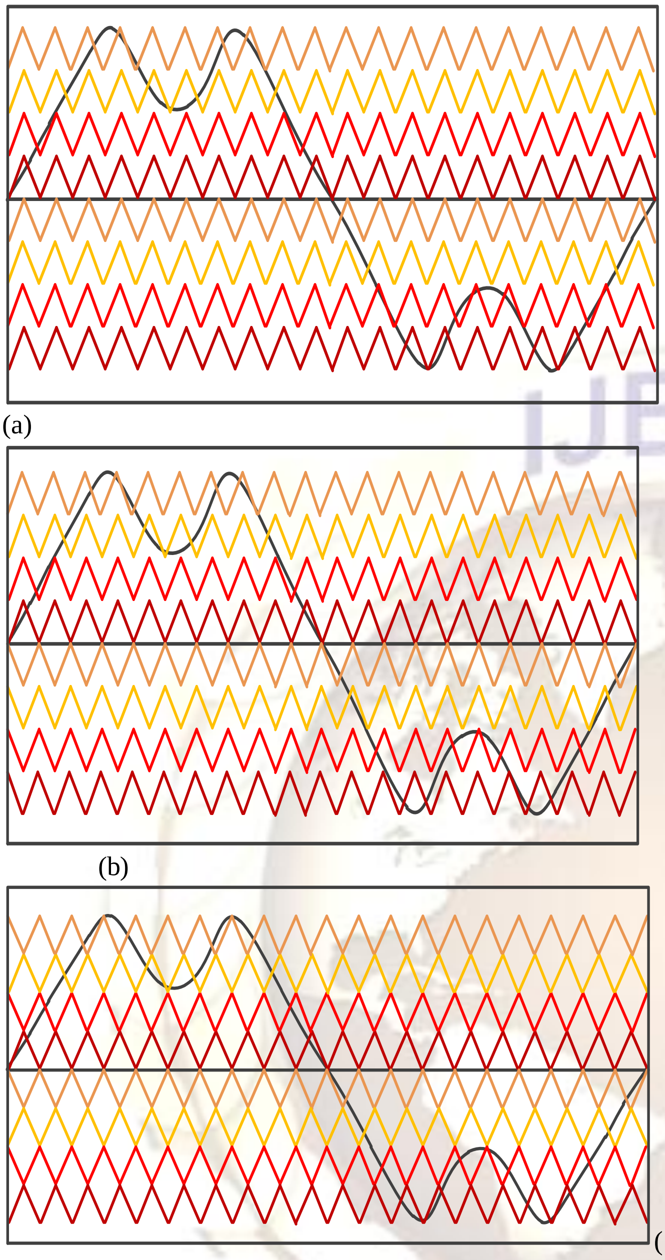
$$V_{cSFO} = V_c - V_{offset}$$

The ability of SFO-PWM technique to product the zero-sequence restricts its implementation to a three-phase three-wire system, but it enables the modulation index to be increased by 15% before pulse dropping occurs[14],[17].

In the switching frequency optimal method, carrier waves are placed in relation to the reference in three situations:

- Phase Disposition Pulse-Width Modulation (PD-SFO-PWM), where all the carriers are in phase.
- Phase Opposition Disposition Pulse-Width Modulation (POD-SFO-PWM), where all the carriers above the zero value reference are in phase among them, but in opposition with those below.
- Alternative Phase Opposition Disposition Pulse Width Modulation (APOD-SFO-PWM), where each carrier band is shifted by 180° from the nearby bands.

PD-SFO-SPWM, POD-SFO-SPWM and APOD-SFO-SPWM respectively show in figure 6a, figure 6b and figure 6c.



(a)

(b)

(c)

Figure 6. (a)PD-SFO-SPWM, (b) POD-SFO-SPWM, (c) APOD-SFO- SPWM

V. VARIABLE SWITCHING FREQUENCY PWM

A- Sub-Harmonic PWM

For a multilevel inverter, if the level is m there will be $(m-1)$ carrier set with variable switching frequency pulse width modulation when compared with third harmonic injection reference [18]. The carriers are in phase across for all the bands. In this technique, significant harmonic energy is localized at the carrier frequency. Since, it is a co-phrasal component; it doesn't appear line to line voltage. In this study a nine level CMCI which levels are $0, \pm\frac{V}{8}, \pm\frac{2V}{8}, \pm\frac{3V}{8}, \pm\frac{V}{2}$, is assigned to have variable switching frequency of 2KHz and 5KHz as shown in figure 7.

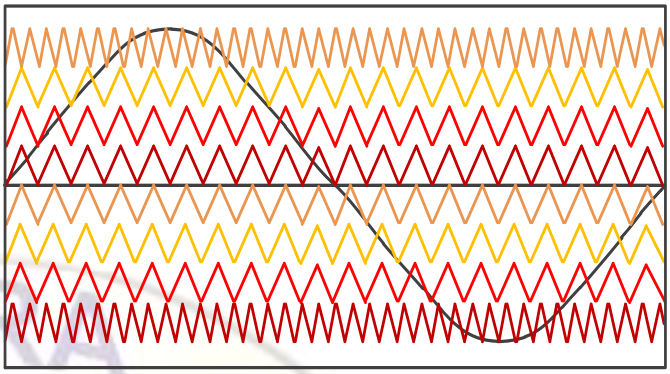


Figure 7. Variable Switching Frequency Sub-Harmonic SPWM

B- Switching Frequency Optimal PWM

For a nine level multilevel inverter, 8 carrier sets with variable switching frequency carrier pulse-width modulation where compared with third harmonic injection reference. For third harmonic injection given as [14], [19]:

$$Y = 1.15\sin\theta + \frac{1.15}{6}\sin 3\theta \quad (6)$$

The resulting flat topped waveform lets over modulation while maintaining excellent AC term and DC term spectra. This is a suggested approach to amend the output voltage without entering the over modulation range. So any carriers used for this reference will improve the output voltage by 15% without increasing the harmonics.

In this study a nine level CMCI which levels are $0, \pm\frac{V}{8}, \pm\frac{2V}{8}, \pm\frac{3V}{8}, \pm\frac{V}{2}$ is assigned to have variable switching frequency of 2KHz and 5KHz as shown in figure 8.

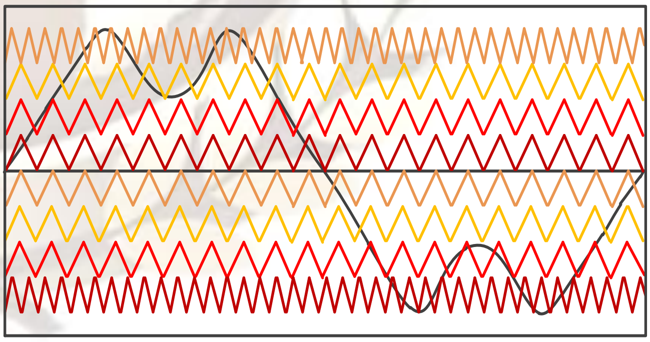


Figure 8. Variable Switching Frequency Optimal SPWM

VI. SIMULATION RESULT

In this paper tree different carrier such as: triangular wave, square wave and sinusoidal waveform, in two methods of Pulse width modulation have been used in order to compare the THD and output voltage level in a nine-level CHMCI.

The simulation circuit shows in figure 9. All legs are in phase and just have different carriers.

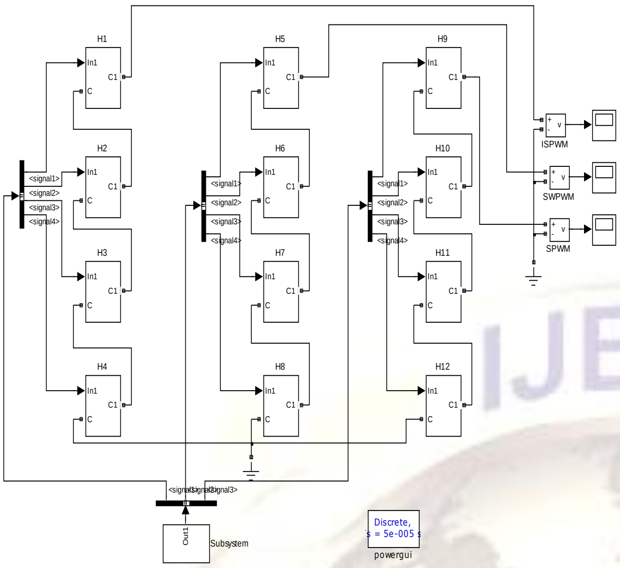


Figure 9. Cascade multicell inverter

Table 2 shows the THD of each approach in order to make better comparison between the above-mentioned methods. Parameters which have been used in simulations for all methods are as follows: $V_{dc} = 100$, $m_a = 1$, $f_m = 60\ Hz$ and $f_c = 5030\ Hz$ Simulation time = 1sec Number of cycle = 60

Table 2. THD for tree different carriers

Modulation Method	SPWM THD%	SWPWM THD%	ISPWM THD%
Constant Switching Frequency (PD SH PWM)	4.63	4.43	3.65
Constant Switching Frequency (POD SH PWM)	4.59	4.39	2.00
Constant Switching Frequency (APOD SH PWM)	4.37	4.19	2.04
Constant Switching Frequency (PD SFO PWM)	39.65	39.63	38.71
Constant Switching Frequency (POD SFO PWM)	39.69	39.63	38.87
Constant Switching Frequency (APOD SFO PWM)	39.46	39.64	38.65
Variable Switching Frequency (SH PWM)	12.66	4.52	3.28
Variable Switching Frequency (SFO PWM)	38.09	39.47	39.17

VII. CONCLUSIONS

In this paper the authors focused on THD comparison in LSPWM methods with three different carriers. The waves that used for carriers are: 1-Triangular wave 2-Sinusoidal wave 3-Square wave. All carriers used in the constant switching frequency PWM and variable switching frequency PWM. According to Table 2 the best method for cascade multicell inverter modulation is Constant Switching Frequency POD SH ISPWM that it has the lowest total harmonic distortion.

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