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A smart cascaded H-bridge multilevel inverter with An optimized modulation techniques increasing the quality and reducing harmonics

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Article Info	ABSTRACT
	The world community relied heavily on fossils energies but just after the big oil crisis the use of renewable energy has greatly increased and has become the main interest of many countries for its many advantages such as: minimal impact on the environment, renewable generators requiring less maintenance than traditional ones and it has also a great impact on economy. It is easy to get charmed by the advantages of using the renewable resources but we must also be aware of their disadvantages. One of the major disadvantages is that the renewable energy resources are intermittent and thus they have led scientists to develop new semiconductor power converters among which are the multilevel inverter. In this paper a new smart multi-level inverter is proposed so as to increase its levels according to the user's needs and also to avoid the impact of shades and the intermittence on photovoltaic panels. We also propose a modification on the multicarrier aiming to reduce the harmonics. This modification introduces a sinusoidal wave compared with trapezoidal multi-carrier to generate the pulses. In order to obtain the line voltages and the total harmonic distortions (THD) MATLAB/SIMULINK is used.

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1. INTRODUCTION

The world around us has changed considerably over the past 20 years. As fossil fuels become more expensive and tougher to find and also because energy fuels related activities have led to significant environmental damages [1]. Thus it is a wiser decision for governments all around the world to reduce their dependency on such traditional types of energy and replace it with other sources of energy that can be safer, cheaper cleaner and renewable, solar energy is undeniably one of these sources, using solar radiation to produce the heat and electricity [2]. Solar energy demand has grown by 25% annually during the past 20 years [3]. However, its utilization has met different difficulties the major ones are power quality and the intermittent of renewable energy resources [4].

Power Quality has been a problem ever since electrical power was invented and in recent years, it has become the main interest of researchers who are still concerned about finding ways to reduce its negative influence on electrical devices. Harmonics are an important factor in power quality and also to maintain stable power supply performance [5], so the inverters with harmonics reduction is required multilevel inverters are gaining celebrity for Photovoltaic (PV) systems due to the reduced total harmonic distortions of the output signal and the low voltage stress of power switches. It produces almost a sinusoidal voltage at the output [6]. In addition, two-level inverters are exposed to thermal stresses created by converting the full

voltage imposed by the continuous source, so the performance and lifetime of its components are actually affected. In this scenario, a new smart multilevel inverter is proposed with a modified command system aiming to reduce more harmonics on the output signal and also it will allow every solar panel in the system to operate independently so the total energy system will not be excessively affected by shades and intermittent. Cascaded H-bridge multilevel is found to be attractive for our smart inverter because it uses the same technology in series "full H-Bridges" to produce inverted AC from separate DC sources [7].

This paper presents a proposition of a smart cascaded h-bridge multi-levels inverter with the possibility of increasing the levels according to the need of the user. Multiple multi-carrier SPWM methods for cascaded h-bridge are analyzed and compared with the conventional SPWM technique. Those carriers are being implemented with different sinusoidal dispositions PD, POD and APOD and with different frequencies.

2.   MULTI-LEVEL INVERTER
2.1. Induction motors
Big electric energies uses include advanced power electronics inverter to encounter the high demands. As a result, multilevel voltage inverter has been presented as an alternative in high power and medium voltage circumstances [8]. A multilevel converter not only attains high power assessments, but also it increases the performance of the whole structure in terms of harmonics [9].Many present schemes incorporate the use of induction motors as main source for traction in electric vehicles, those driver require advanced power electronic inverters, to attain their high power demands.

The multilevel voltage inverters structure allows them to grasp this high voltage requirement without the usage of transformers [10], especially high voltage vehicle drives where electromagnetic interference (EMI) and low total harmonic distortion (THD) of the output voltage are vital.

The general utility of the multilevel inverter is to create a desired voltage from multiple levels of dc voltages, for this reason, multilevel inverters can easily deliver the high power necessary to large electrical Vehicles, hybrid Vehicles or any motor inverter technology used mainly in areas of high energy consumption such as air conditioning.

Cascade inverters are perfect for an induction motor this configuration gives many advantages such as [11]:
a) It makes induction motor safer /handy for induction motor power system.
b) No electromagnetic interference.
c) Higher efficiency is attained compared to low voltage motors.
d) Low voltage switching devices are used.
e) No unbalance charge problem in drive mode or charge mode.

2.2. Basic structure
A cascaded multilevel inverter is a power electronic device made to create a desired AC voltage from several of DC voltages the structure is composed of several H-bridges converters in series connection as given in Figure 1 it got many advantages it can reach high voltage and high power without transformers and with a remarkable improvement of the spectral quality [12] .

The voltage levels L of the cascaded H inverter is defined by L = 2N+1, where N is the number of DC sources

The more H inverters are used the more levels of the output waveform are created and the shape becomes approximate to sinusoidal waveform.

The output voltage can be expressed as:

Vout = V1 + V2 + V3 + …..+Vn . Each full bridge inverter can generate three levels -Vdc, 0 and +Vdc.
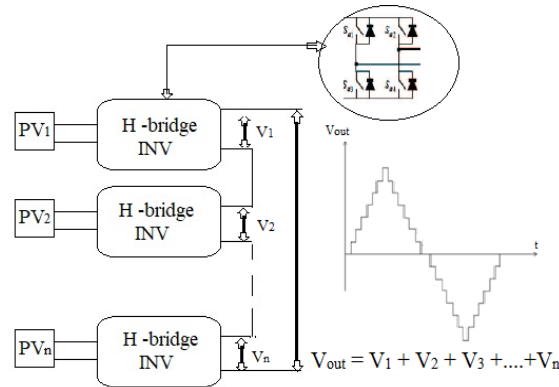
Figure 1. Structure of a Cascaded H Bridge

2.3. Carrier-based modulation schemes

Most carrier-based PWM schemes for cascaded H-bridge multi-level inverters descend from the carrier disposition scheme [13] For an L level cascaded inverter, L-1 triangular carriers is used with the same frequency and amplitude so that they fully occupy the range [14]. A single reference sinusoidal signal with low frequency is been continuously compared with each carrier to determine the switched device.

Three carrier disposition PWM strategies are well known and referenced [15]:
a) Phase disposition (PD), carriers are in the same phase Figure 2.
b) Phase opposition disposition (POD), carriers above zero are 180° phase shifted with those below
c) Alternative phase opposition disposition (APOD), where the carriers are alternately 180 ° phase shifted

In this paper, different multi-carrier shapes (Triangular, Trapezoidal) are used and the performances are analyzed to prove the best techniques [16]

The results are obtained when using those techniques with different sinusoidal dispositions PD PWM, POD PWM and APOD PWM.
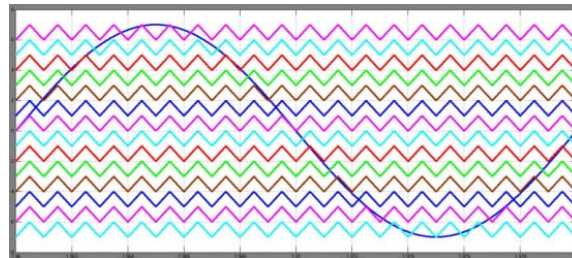

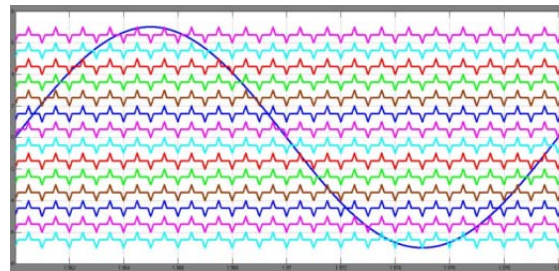Figure 2(a). Triangular multi-carriers with Phase disposition (PD) arrangement

Figure 2(b). Trapezoidal multi-carriers with Phase disposition (PD) arrangement.

The equation (1) for trapezoidal carrier can be inserted in DSP defined as:
Where A is the amplitude and T is the period of the carrier signal.

$$U(t) = \begin{cases} \frac{t}{t1}\left(\frac{A}{2}\right) & 0 \leq t < t1 \\ A/2 & t1 \leq t < t2 \\ \left[\frac{t-t2}{t3-t2}\right]\left(\frac{A}{2}\right) + A/2 & t2 \leq t < t3 \\ \left[\frac{t4-t}{t4-t3}\right]\left(\frac{A}{2}\right) + A/2 & t3 \leq t < t4 \\ A/2 & t4 \leq t < t5 \\ \left[\frac{t-t6}{t5-t6}\right]\left(\frac{A}{2}\right) & t5 \leq t < t6 \end{cases} \tag{1}$$

3. THE TOTAL HARMONIC ANALYZE

The total harmonic distortions (THD) are evaluated through all the modulation techniques and for various frequencies.

To acquire the spectrum of the output voltage (THD) Fast Fourier Transform (FFT) is applied [17]. The THD is calculated using the following equation (2) [18]:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} v_n^2}}{v_1} \tag{2}$$

Where:
n is the harmonic order.
v_n is the root mean square (RMS) value of the nth harmonic component .
v_1 is the (RMS) value of the fundamental component.
The output voltage wave-forms Figure 3 and the total harmonic distortions Figure 4a,b are acquired for both types of multi-carriers.
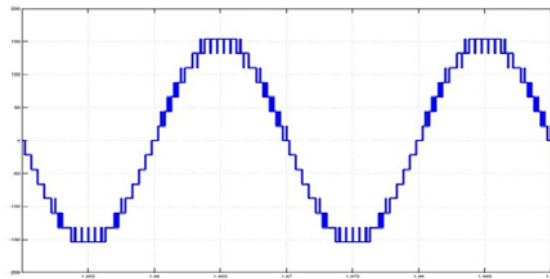

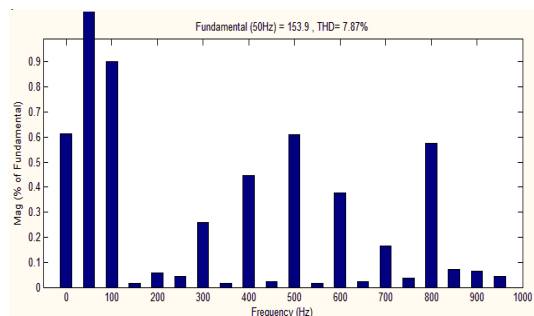Figure 3. The output voltage wave-forms

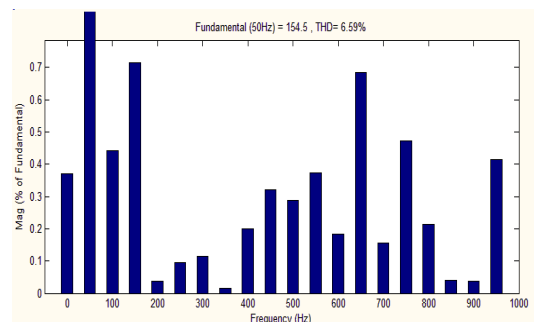Figure 4 (a). FFT Analysis of the Output using Triangular carriers

Figure 4 (b). FFT Analysis of the Output using modified Trapezoidal carriers

The Table 1 resumes all harmonics distortion results for both multi-carrier techniques with different frequencies.

Table 1. The harmonic distortion analyses.

Techniques	Dispositions / Frequencies	Phase Dispositions	Phase opposite disposition	Alternative phase opposite disposition
Triangular	1 KHz	8.27%	8.28%	9.45%
	2 KHZ	7.87%	8.68%	8.14%
Trapezoid	1 KHz	6.71%	7.39%	7.20%
	2 KHZ	**6.59%**	7.06%	6.74%

It confirms that the best performance for triangular carriers is when phase disposition with 2 KHz frequency is used and after using the trapezoidal carriers better results are obtained with a gain of 1.28%.

So it is clear that this new modification is best suited for Cascaded Multi-Level with the improvement of the output signal quality which makes it more suitable for both standalone and grid connected systems.

4.   SMART MULTI-LEVEL INVERTER

4.1. Shades

In most solar photovoltaic (PV) systems it contains about 6 to 30 panel [19], to encounter the voltage necessities of the system's inverter, solar arrays are usually alienated into strings of solar panels but those strings are usually consisted form more than one single panel [20].

If shade is on even one of the panels in the string, the output of the entire string will be reduced to nearly zero [21] for as long as the shadow stands there. In some cases, a shadow does not essentially need to descent on a whole panel, even just one cell could crush the output of the panel and turn off the entire string and becomes a receiver that will heat up and lead to a loss of production or even worse Figure 5 [22].
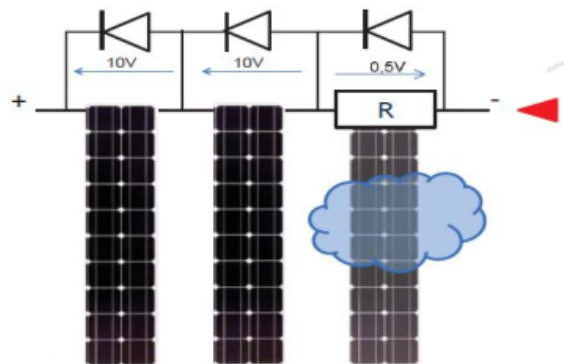

Figure 5. Effect of shades on photovoltaic panels

The smart multilevel inverter Figure 6 proposed in this paper will have the possibility of increasing levels of the output according to the need of the user mainly according to the number of continuous DC sources available and also according to the power desired. In this way it will allow every solar panel in the system to operate independently and the total energy system will not be excessively affected by any shaded panels and at the same time it can be replaced by a storage battery.

The user will have multiple of h-bridge cards Figure 7, those cards can be inserted in another card with slots to increase the levels; the number of inserted card must be the same as the continuous sources disposed.
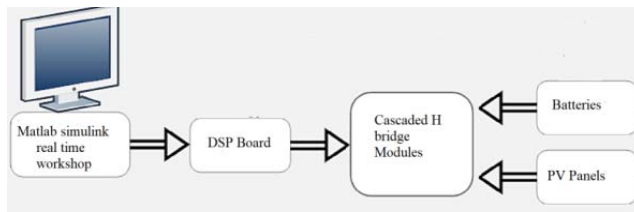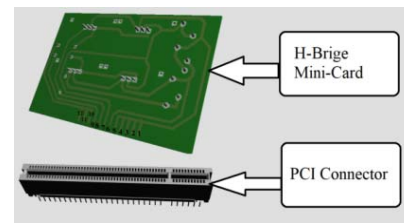
Figure 6. Smart cascaded system   Figure 7. H-bridge cards

4.2. H-bridge with driver

An output pulse (+ 5v) of a microcontroller is generally sufficient to drive a MOSFET dedicated to small signal. However, two problems arise when working with more powerful MOSFETs:

• The control signal of the 3.3 V or 5 V microcontrollers is not often enough. It is necessary to apply at least 8-12V to completely ignite the MOSFET which can cause their destruction [23].

• Without drivers MOSFET switching can cause a feedback to the control circuit, while the drivers are designed to handle this problem [24].

Since we will convert voltages higher than + 30V we will need drivers (IR2304) in our circuits ,it will maximize the switching speed by injecting current so that the MOSFET spends the least possible time in transition time, and so we will have a minimum waste of energy and heat on components [25].

For simulation purposes, Proteus ISIS was used Figure 7 to simulate the H-bridge system alongside the MOSFET drivers, with microcontroller programming and all switching devices.
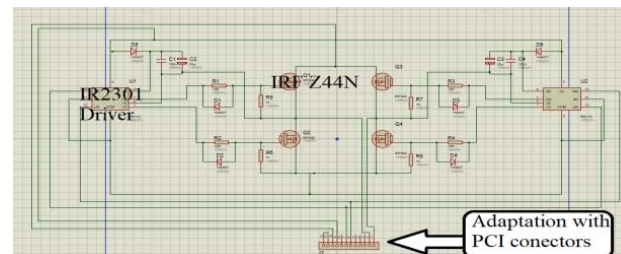

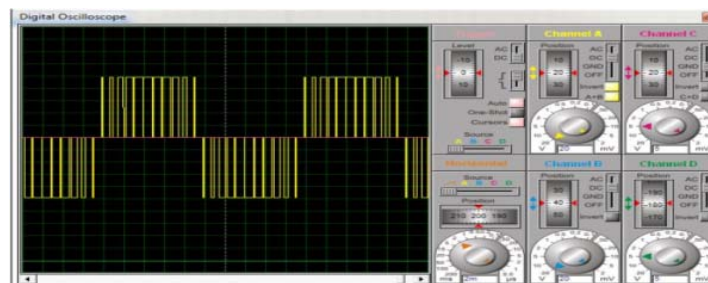Figure 8. H Bridge with MOSFET Drivers

Figure 9. The output voltage of the H-bridge inverter

5. EXPERIMENTAL RESULTS

As for Experimental results, the output voltage designed for the system is 230 AC supply Figure 9c. In order to reach it the input supply used is 34V for each different inverter stages, for all switching devices MOSFETs IRF 44ZN are utilized in order to obtain high efficiency over an extensive load range. The DSP controller or arduino-mega is used to generate the switching pulses for switches based on POD, APOD and PD arrangements for PWM. The carrier signals above and below zero are levels shifted to realize PD, POD

and APOD signals. And to generate the pulses required for the MOSFET switches these signals are been compared continuously with the reference sinusoidal signal.

When the inverter starts working, the microcontroller generates a 5v signal to detect the number of cards inserted. Then, a code of 7 digits received will be equivalent to the number and the location of each card. For example, the reception of 0000001 code means that only one card is inserted and the location of the card is in the first slot.

After the testing, the program to produce the switching pulses will be generated corresponding to the code listed and will keep functioning until the inverter's shutdown. As for relays Figure 9 it will let the current flow if there is no h-bridge card inserted. For every h-bridge card the following equipment's Table 2 is needed:

Table 2. H-bridge Materiels.

Quantities	Materials
4	10R Resistors
4	1k Resistors
2	33uF/16v capacities
2	IR2304 Drivers or IR2301
4	IRF Z44N Transistors
6	1N4007 Diodes

The experimental prototype is illustrated on Figure 10(a) along with the PCB layout for every h-bridge card:

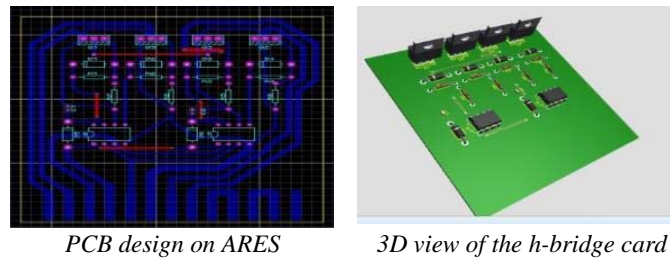*PCB design on ARES*   *3D view of the h-bridge card*

Figure 10(a). PCB layout for h-bridge cards

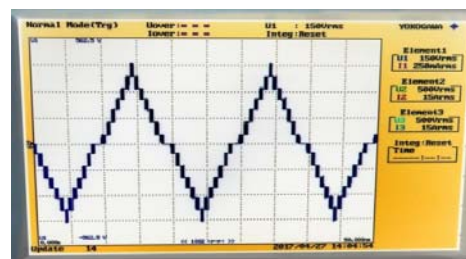Figure 10(b). Suggested smart multi-level inverter

Figure 10(c). Voltage output of fifteen multi-level inverter

According to this system, Phase disposition multi-carrier modulation techniques are used and the output and the performances are analyzed. Figure 10(b) shows the suggested smart multi-level inverter system made up to analyze the performances of a cascaded fifteen levels inverter.

This system is devised into four major parts:

Part 1: Pulses Inputs, where Multi-carrier PWM techniques are inserted (The Command part)

Part 2: DC inputs where, Photo-voltaic DC sources or batteries are used (DC inputs)

Part 3: Relays will let the current flow if there is no h-bridge card inserted.

Part 4: The output voltage after DC conversion (AC output).

For experimental application. The PWM scheme was executed in MOSFETs IRFZ44N using an Arduino Mega 2560 and for better comparison, the same configurations are used in the simulation and experimentation. The output voltage waveform is shown in Figure 10(c). It can be seen that the experimental result match with simulation. A comparison between the cascaded topology of a seven and a fifteen multi-level inverter is done and the results are shown in Table 2, Figures 11(a-j) which clearly shows the percentage reduction in the total harmonic distortion by increasing the number of levels "N".

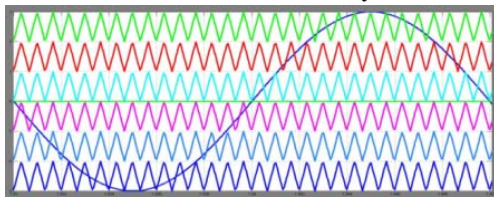**Seven level inverter analyses**

Figure 11(a). Multi-carriers PD arrangement for a seven level inverter
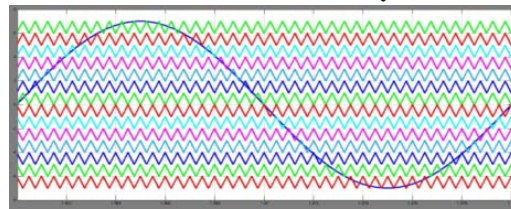
Fifteen level inverter analyses

Figure 11(f). Multi-carriers POD arrangement for a fifteen level inverter
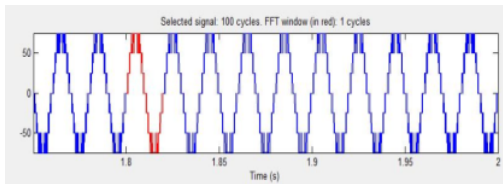

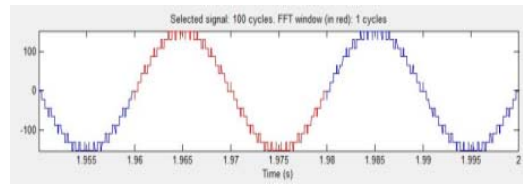Figure 11(b). Seven multi-level inverter output signal

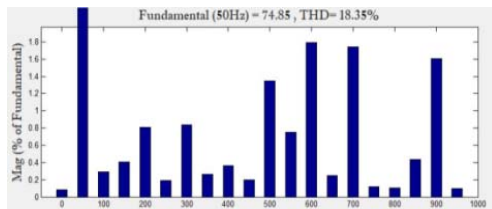Figure 11(g). Fifteen multi-level inverter output signal

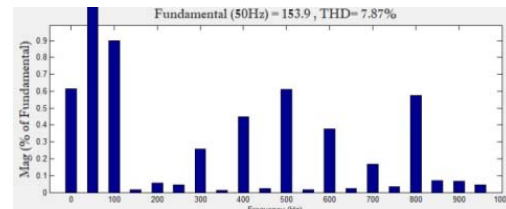Figure 11(c). Seven multi-level inverter THD analysis of POD

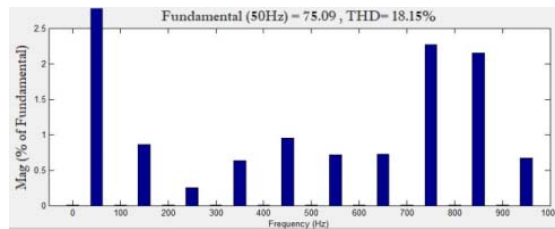Figure 11(h). Fifteen multi-level inverter THD analysis of PD

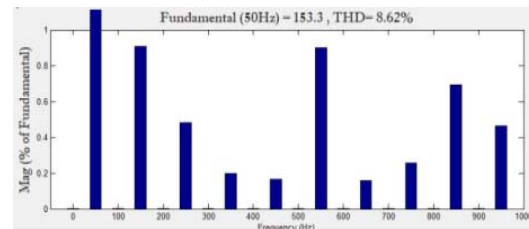Figure 11(d). Seven multi-level inverter THD analysis of APOD

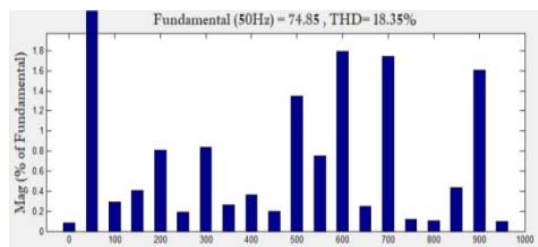Figure 11(i). Fifteen multi-level inverter THD analysis of POD

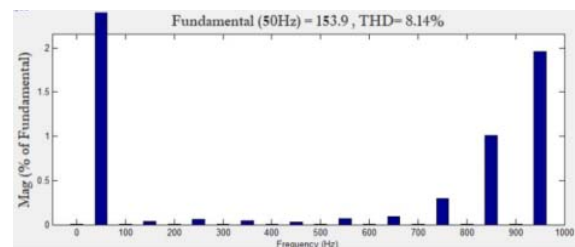Figure11(e). Seven multi-level inverter THD analysis of APOD

Figure 11(j). Fifteen multi-level inverter THD analysis of APOD

6.   RESULTS INTERPRETATION

About DC/AC conversion, the harmonic analysis of output voltages is shown in Figure 12, the fifteen levels inverter generates less Total Harmonic Distortion (THD) and higher output quality for every multi-carriers technical disposition (PD, POD, APOD). Based on obtained results increasing the number of "N" level increases greatly the quality of the output signal by reducing the total harmonic distortion so it clear that increasing levels makes it more suitable for applications where electromagnetic interference (EMI) and low total harmonic distortion (THD) of the output voltage are vital.

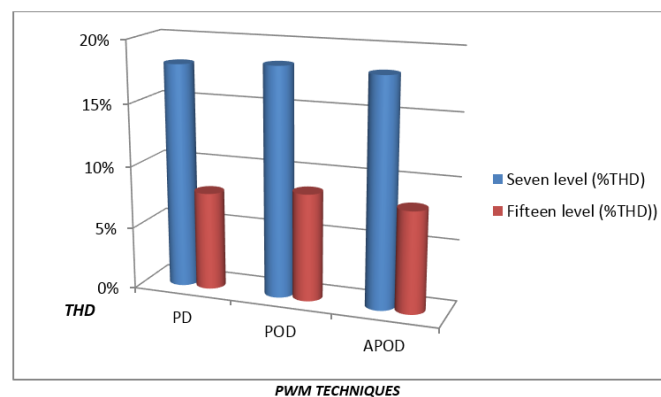

Figure12. THD analysis for the line voltages

7.   CONCLUSION

The SPWM control scheme for the fifteen level cascaded H bridge inverter has been presented in this paper The PD PWM method has given the better results for all types of carriers, The results illustrate that after modifying the carriers better results can be obtained.

    The smart multilevel inverter suggested will allow every solar panel in the system to operate independently and the total energy system will not be extremely affected by shades or some intermittence.

    A comparative study of a seven and fifteen multi- level inverter is done to illustrate the great improvement of the quality signal due to the N level of the multi-inverter.

    It is clear that this new scheme is best suited for Cascaded Multi-Level with the improvement of the output signal quality which makes it more suitable for both standalone and grid connected systems.

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