Implementation of Digital Controller TMS320C28027 to MPPT Based Single Phase Bidirectional High Frequency Link Inverter for Photovoltaic Applications

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Abstract- Various digital technologies are being implemented in photovoltaic inverter in order to acquire higher efficiency and to lower total harmonic distortion. In this paper a new topology of implementation of digital controller TMS320C28027 to bidirectional high frequency link photovoltaic inverter has been proposed for photovoltaic application using perturb and observation method. The proposed scheme is simulated and experimentally validated by obtaining the values of total harmonic distortion and efficiency.

Keywords- Purturb and observe, insolation, unipolar switching, boost converter

1. Introduction

With the growing energy demand, increasing global environmental issues, and depleting energy resources such as coal, oil and gas, the need to develop and utilize new sources of energy seems inevitable. Therefore renewable energy resources such as solar, wind, biomass, hydro and geothermal etc appear as important alternative energy options. Solar energy is one of the few clean and abundant renewable energy resource which is being use extensively in recent years. Worldwide lot of work on solar technology is going on even in the countries where there is limited sunshine over the year. With the advancement in control techniques, solar energy is becoming one of the alternate renewable energy sources for generation of power [12],[16]. The recent trend of designing inverter with high efficiency, compact, light weight and low cost is based on the parameters such as lowering total harmonic distortion, increasing switching frequencies, improving voltage and current waveforms and power factor[5],[13]. In order to achieve these requirements, digitally controlled high-frequency link photovoltaic inverter with bidirectional power flow capability has been developed using MPPT control and boost converter. The overall system is represented by block schematic as shown in fig 1.
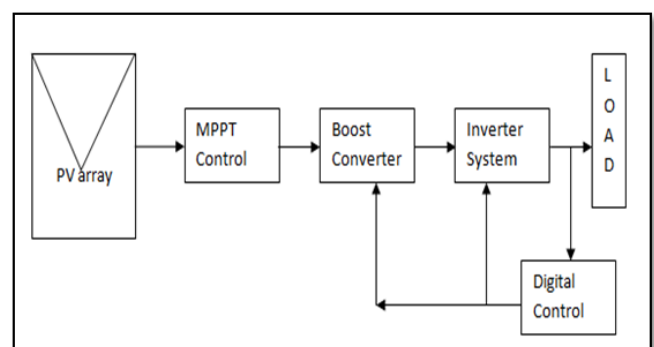
Fig. 1. Basic block of photovoltaic inverter system

2. Purturb and Observe (P&O) method

There are various methods for tracking such as open circuit voltage, constant voltage, short circuit current,

incremental conductance method and puturb and observe method [3],[7]. The method used in this topology is P&O method which is more convenient to use. In this method, calculation of photovoltaic array output is done with power change done by sensing both photovoltaic voltage and current. This method also considers the perturb amplitude to the actual operating condition. Considering a solar cell, the VI characteristics neglecting the shunt resistance is given by the equation

$$V = \frac{AKT}{q}\left(\frac{I - I_{ph} - I_{sat}}{I_{sat}}\right) - r_s I \tag{1}$$

Where I_{ph} = Current generated from photons

I_{sat} = reverse saturation current
q = charge on electron, A = Ideality factor,
K = Boltzmann's constant, T = Temperature,
r_s = series resistance

The light generated current and saturated reverse current is expressed as

$$I_{ph} = [I_{scr} + K_I(T - T_r)]S \tag{2}$$

$$I_{sat} = I_{rr}\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_g}{K}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \tag{3}$$

Where T_r = reference tempreture,

I_{scr} = short circuit current at reference tempreture
K_I = current tempreture coefficient,
S = per unit radiation,
I_{rr} = reverse current at reference tempreture

In order to find the value of voltage at maximum peak power the power derivative of current function is zero and for current voltage function is zero. Thus maximum power is calculated by the following eqauation

$$\frac{AKT}{q}\ln\left(\frac{I - I_{ph} - I_{sat}}{I_{sat}}\right) + \left(\frac{AKT/q}{I - I_{ph} - I_{sat}}\right) - 2r_s = 0 \tag{4}$$

Based on the equation for P&O method an algorithm is developed in MATLAB. The fig.2 shows the MATLAB/Simulink model for P&O method.
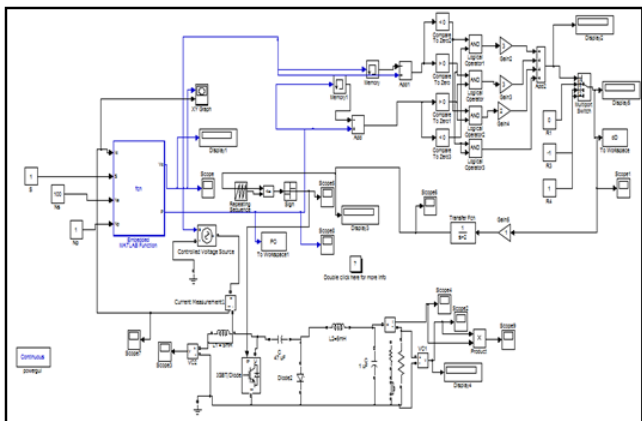
Fig 2. Simulink model for boost converter using P&O method

## 3. MATLAB/Simulink Model of a Closed Loop System with Boost Converter

In order to achieve higher efficiency a model of photovoltaic system was realized with closed loop control as shown in fig.3. The PV panel has been considered based on the irradiance, temperature, open circuit voltage and short circuit current. The result of closed loop boost converter was studied based on the variation in insolation as well as varying load [4].
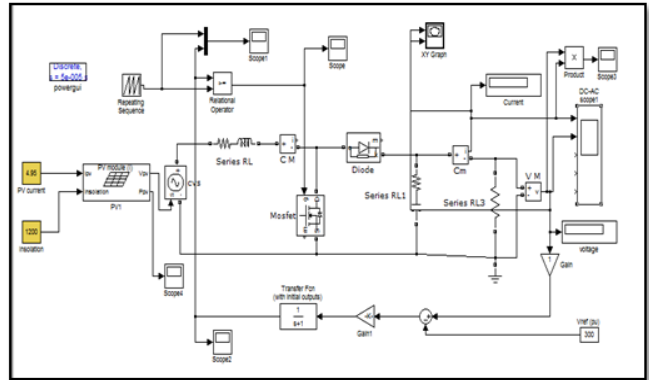
Fig. 3. Closed loop boost converter

4. Mathematical Modeling of BHFL Photovoltaic Inverter

Different types of inverter topologies were studied by developing and simulating in MATLAB/Simulink [9], [15], [17]. To design a closed-loop controller for the BHFL inverter as shown in fig.4, a dynamic model of the BHFL inverter is first derived. State-space technique is used to model the inverter [8].
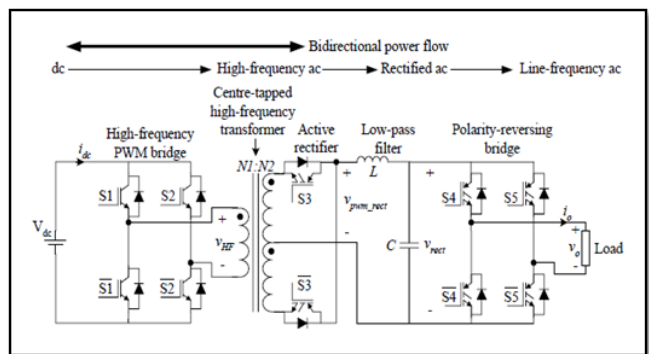
Fig. 4. Bidirectional High Frequency Link Inverter

Referring to fig 4, it is assumed that the dc source voltage, V_{dc} is constant. The inverter switching frequency is considered to be much higher than the 50Hz sinusoidal modulating frequency. The high-frequency transformer is assumed to be operating in the linear area. As such, the high-frequency PWM bridge and the transformer can be modeled as constant gains [14]. The polarity-reversing bridge is only operated at line-frequency (50Hz), thus its dynamics can be ignored. With these assumptions, the dynamics of the system can be simplified to a *LC* low-pass filter connected to the load. The equivalent circuit of the BHFL inverter could be

considered, where u is the system input (control variable), and Z denotes the output impedance of an unknown load. The Equivalent Series Resistance of the filter inductor is denoted as r_L, and the ESR of the filter capacitor is denoted as r_c.

$$\frac{di_l}{dt} = -\frac{1}{L}(r_l + r_c) - \frac{1}{L}V_{rect} + \frac{1}{L}v + \frac{r_c}{L} \qquad (5)$$

$$\frac{dv_{rect}}{dt} = \frac{1}{c}i_1 - \frac{1}{c}i_{or} \qquad (6)$$

Also

$$V_{or} = r_c + V_{rect} - r_c i_{or} \qquad (7)$$

Equation 5 and 6 can be represented in matrix form as

$$\begin{bmatrix} \frac{di_l}{dt} \\ \frac{dv_{rect}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}(r_l + r_c) & -\frac{1}{L} \\ \frac{1}{c} & 0 \end{bmatrix} \begin{bmatrix} i_l \\ v_{rect} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v + \begin{bmatrix} \frac{r_c}{L} \\ -\frac{1}{c} \end{bmatrix} i_{or} \quad (8)$$

Also equation 7 can be expressed as

$$v_{or} = [r_c \quad 1] \begin{bmatrix} i_l \\ v_{rect} \end{bmatrix} + [-r_c] i_{or} \qquad (9)$$

the values of r_l & r_c are assumed to be very small & can be neglected .Thus equation 8 & 9 becomes

$$\begin{bmatrix} \frac{di_l}{dt} \\ \frac{dv_{rect}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{c} & 0 \end{bmatrix} \begin{bmatrix} i_l \\ v_{rect} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v + \begin{bmatrix} 0 \\ -\frac{1}{c} \end{bmatrix} i_{or} \qquad (10)$$

$$v_{or} = [0 \quad 1] \begin{bmatrix} i_l \\ v_{rect} \end{bmatrix} \qquad (11)$$

Based on the equation a dynamic model of the system could be represented by block diagram. Since the controller is to be implemented using a digital processor ,the continuous time space equations are discretised .The discrete time state space equations with sampling period of T_s can be represented as

$$x(k + 1) = Ax(k) + Bu(k) + B_d i_{or}(k)$$

$$v_{or}(k) = Cx(k)$$

Where

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = \begin{bmatrix} \cos(wT_s) & -\frac{1}{wL}\sin(wT_s) \\ \frac{1}{wc}\sin(wT_s) & \cos(wT_s) \end{bmatrix}$$

$$B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{wL}\sin(wT_s) \\ 1 - \cos(wT_s) \end{bmatrix}$$

$$B_d = \begin{bmatrix} B_{d_1} \\ B_{d_2} \end{bmatrix} = \begin{bmatrix} 1 - \cos(wT_s) \\ -\frac{1}{wc}\sin(wT_s) \end{bmatrix}$$

$$c = [0 \quad 1]$$

$$x(k) = \begin{bmatrix} i_1(k) \\ V_{rect}(k) \end{bmatrix}$$ is the state vector & w = 1/√LC is the cut off frequency of the low pass filter in radians/second.

From equation 10 and 11, the discrete time equation can be rewritten as:

$$u(k) = \frac{1}{B_1}i_l(k + 1) - \frac{A_{11}}{B_1}i(k) - \frac{A_{12}}{B_1}v_{or}(k) - \frac{B_{d_1}}{B_1}i_{or}(k) \quad (12)$$

$$i_L(k) = \frac{1}{A_{21}}v_{or}(k + 1) - \frac{A_{22}}{A_{21}}v_{or}(k) - \frac{B_2}{A_{21}}v(k) - \frac{B_{d_2}}{A_{21}}i_{or}(k)$$
$$(13)$$

The equations 12 and 13 represent the discrete model of BHFL inverter system.

5. MATLAB/Simulink Model of BHFL Photovoltaic Inverter

The MATLAB/Simulink model of BHFL photovoltaic inverter was developed with unipolar switching technique which was used to control the magnitude and frequency of generated ac signal. The fig.5 shows the MATLAB/Simulink model of single phase BHFL solar photovoltaic inverter with unipolar switching [18].
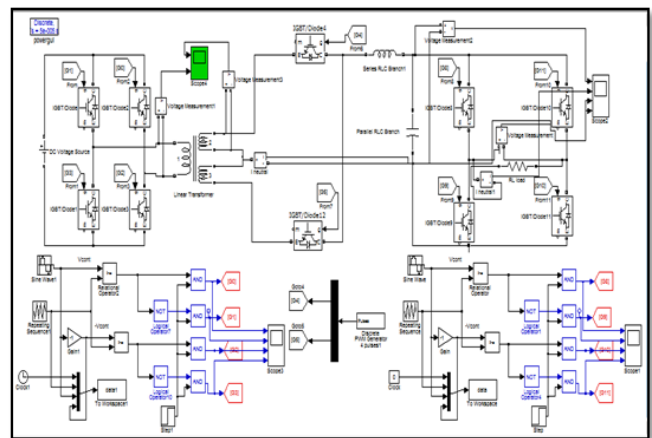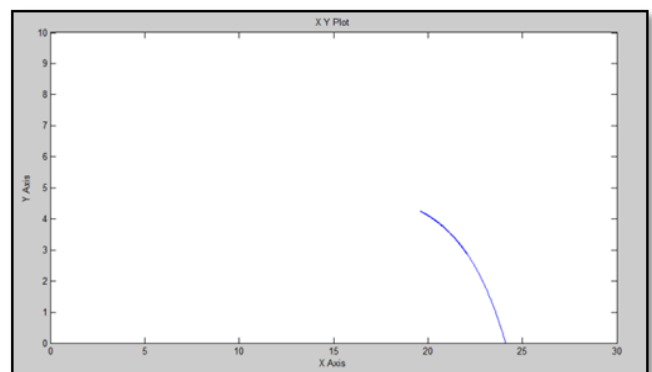

Fig. 5. Single phase IGBT based BHFL Solar PV inverter
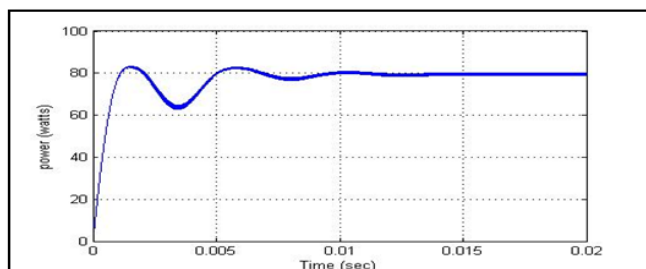
6. Simulation Result

Considering the MATLAB/Simulink model for P&O observation method an MPPT curve was obtained whisch extracted the maximum value of voltage and current for maximum power as shown in fig.6.

(X-axis – Voltage, Y-axis- Current)

Fig. 6. MPPT Curve

A steady state power curve was also obtained from the model as shown in fig.7.

Fig. 7. Power Characteristics

The MATLAB/Simulink model of boost converter with closed loop system was tested with various values of insolations as well as rated values of solar panels as shown in table 1.1 and table1.2.
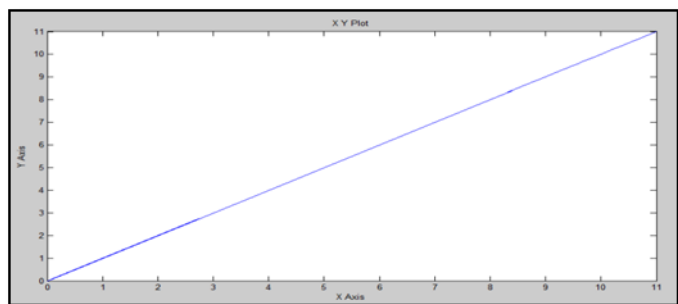
No.	(w/m^2)			Power(watts)
1)	925	3.914	3.914	15.32
2)	950	9.769	9.769	95.43
3)	975	10.57	10.57	111.8
4)	1000	10.93	10.93	119.4
5)	1025	11.15	11.15	124.4
6)	1050	11.32	11.32	128.2
7)	1075	11.45	11.45	131.2
8)	1100	11.56	11.56	133.2
9)	1125	11.65	11.65	135.8
10)	1150	11.74	11.74	137.7
11)	1175	11.81	11.81	139.4
12)	1200	11.87	11.87	140.9
13)	1340	12.16	12.16	147.9

Table 1.1. Output power based on insolation

Sr.	Insolation	$I_{out (Amp)}$	$V_{out (Volts)}$	Output

Table 1.2. Power output based on standard panels

SN	Model No.	Isc Amp	Voc volt	Imax Amp	Vmax volt	Pmax Watts	Ipv Amp	Vpv volt	O/P Power (W)
1	BP3230T	8.4	36.7	7.9	29.1	230	18.8	18.8	355.5
2	BP3225T	8.3	36.6	7.7	29.1	225	18.8	18.8	355.5
3	BP3170T	5.2	43.6	4.8	35.6	170	23.2	23.2	537.5
4	BP3215T	8.1	36.5	7.4	29.1	215	18.8	18.8	355.5

Considering the values of insolation equal to 1000 watt/m^2 , I_{sc} = 5.45 amp, V_{oc}= 22.5 volts, Ip_{max}= 4.95, Vp_{max}= 17.2 volts, the V-I and power characteristics were studied as shown in fig 8 and fig.9.

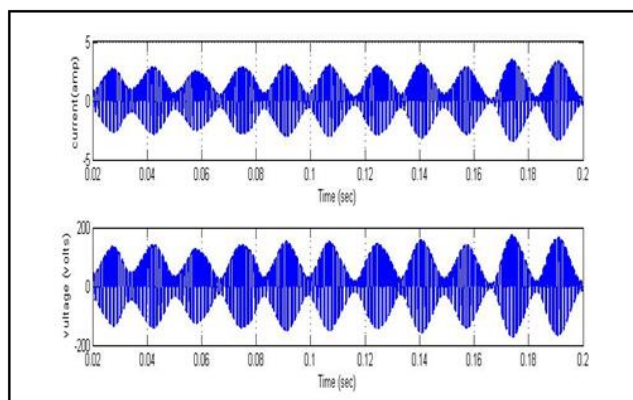
(X axis – voltage, Y-axis – current)
Fig. 8. V-I Characteristics
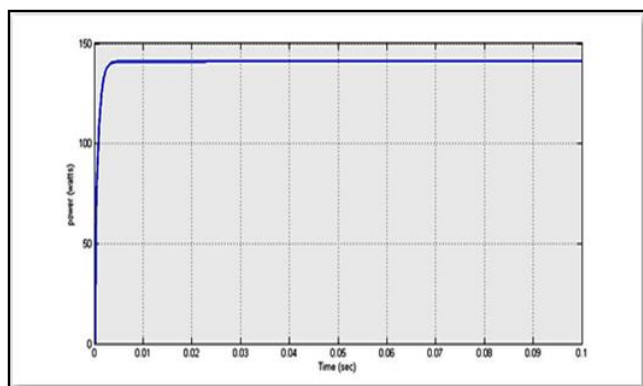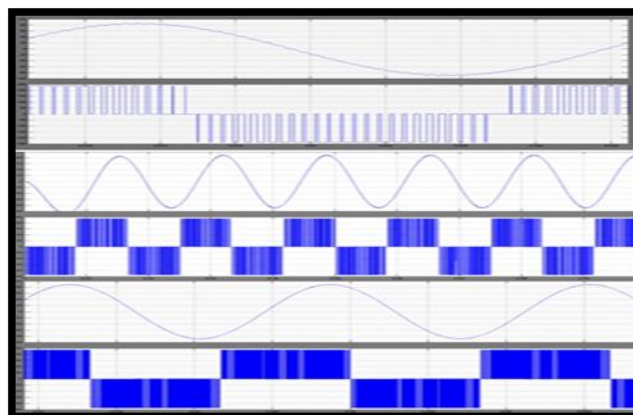

Fig. 9. Power Characteristics

The current and voltage waveforms for BHFL photovoltaic inverter were observed as shown in fig.10

Fig. 10. Current and Voltage Characteristics

The output of BHFL photovoltaic inverter was also tested with different switching frequencies as shown in fig.11

Fig. 11. Output signal and PWM with f_c = 1.5 KHz, 2.5KHz and 10 KHz

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7. Generation of PWM signal using TMS320C28027

Generation of PWM signal is based on the performance of digital signal processor [1], [2], [6]. For this, processor TMS320C28027 of Texas Instrument has been selected. It is a piccolo series processor which is coupled with highly integrated control peripherals in low pin count devices. It is a high efficiency processor with 32 bit CPU and having frequency of 60MHz, 50MHz and 40MHz respectively. It is also having ON-Chip flash, SARAM and OTP memory. It consists of analog comparators with 10 bit reference and can be routed directly to control PWM outputs [10]. This processor is also cheaper and easy to implement. Generation of PWM signal is based on implementation of algorithm, preparing of source code in C or C++ and compiling, building and running the source code in code composer studio.

The version used for code composer studio is 3.1 and the PWM signal has been generated at 8 GPIO pins i.e from GPIO0 to GPIO7 by continuously comparing the output voltage or current received by inbuilt ADC. The PWM signals generated from GPIO pins are applied to the IGBT's of inverter circuit through a driver circuit [11].

8. Experimental Setup

Based on the results obtained from MATLAB/Simulink models, a hardware prototype of 500VA BHFL photovoltaic inverter was developed by considering digital controller TMS320C28027 for controlling the power switches. Fig 12 shows the hardware proto type of PWM generation, digitally controlled BHFL photovoltaic inverter, and output AC signal.
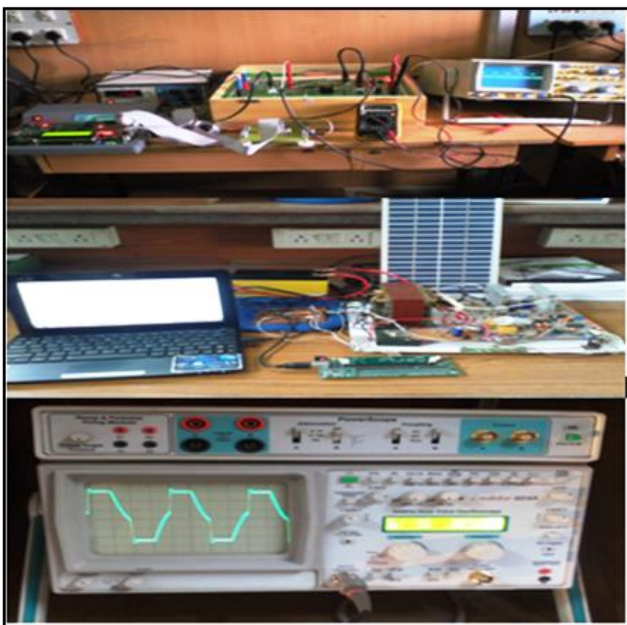

Fig. 12. PWM generation, BHFL photovoltaic inverter, output signal

9. Conclusion

Modeling and experimentation using TMS320C28027 for 500 VA single phase BHFL photovoltaic inverter with MPPT was studied and compared. The V-I characteristic observed tracks for the maximum power and stabalises the output power. The boost converter with closed loop system was tested with various values of insolations ranging from 925 watt/m^2 to 1340 watt/m^2 and it was observed that with increase in insolation values the output power was also increasing. This model was also tested with some standard ratings of the panels available used in prototype.

Based on the output generated by the closed loop boost converter, a MATLAB/Simulink model of BHFL photovoltaic inverter was developed and its output was studied by considering different switching frequencies. It was observed that by increasing the switching frequencies there is an improvement in output signal. The amount of THD for single phase BHFL photovoltaic inverter was found to be 4.95% as shown in fig.13.
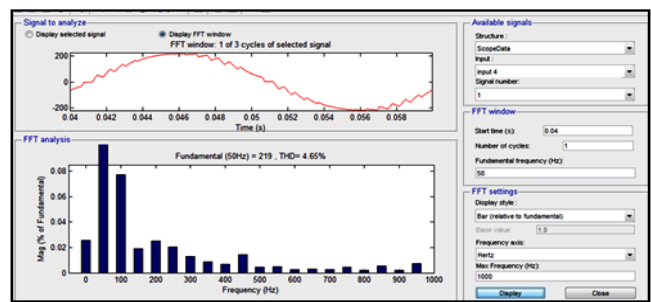

Fig. 13. THD obtained

The voltage waveform generated by the prototype hardware model was a quasi squre wave with a THD of 6.23%. Further improvement could be done by considering TMS320C28027 for single phase multilevel photovoltaic inverter.

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