Single Phase Multilevel Inverter for Photovoltaic System

D. Durairaj and Dr. K. Rajambal., M.E., Ph.D.,
Department of Electrical Drives and Control
Pondicherry Engineering College
Puducherry

***Abstract*— This paper presents a single phase seven-level inverter for stand-alone Photovoltaic (PV) system with Pulse Width Modulation (PWM) control scheme. Three reference signals that are identical to each other with an offset value equivalent to the amplitude of the carrier signal were used to generate PWM signals for the inverter switches. The inverter is integrated with PV array and a DC/DC boost converter which acts as a DC source. It is capable of producing seven output voltage levels such as (V_{dc}, $2V_{dc}/3$, $V_{dc}/3$, 0, $-V_{dc}/3$, $-2V_{dc}/3$ & $-V_{dc}$) from the DC bus. The performance analysis of the PV inverter system is analysed in detail under open loop condition. Two conventional controllers are used to maintain the DC bus voltage and the inverter output voltage constant. Suitable filters are added to make the current injected to load as sinusoidal. The integrated system is modeled and verified through simulation and results are discussed.**

***Index Terms*—Stand-alone, Multi-level inverter, Photovoltaic system, Pulse-Width Modulation, duty ratio and modulation indices**

I. INTRODUCTION

THE demand for renewable energy has increased significantly over the years because of shortage of fossil fuels, the ever increasing energy consumption and exhaustible nature. Among various types of renewable energy sources, solar energy has become very popular and demanding due to advancement in power electronics techniques. Photovoltaic (PV) sources are used today in many applications as they have the advantages of being maintenance and pollution free. PV inverter, which is the heart of the PV system, is used to convert DC power obtained from the PV modules into AC power which is fed to the loads without any battery storage during day time.

A single phase inverter is usually used for residential or low power applications of power ranges that are less than 10KW [1]. Different types of single phase multi-level inverters are discussed elaborately in [2]-[4]. Various topologies for multilevel inverters have been proposed over the years. Common ones are diode-clamped [5]-[8], flying capacitor [9]-[11], cascaded H-bridge [12], [13] and modified H-bridge multilevel [14]. A common topology of inverter is the full-bridge three-level can satisfy all specifications through its very high switching rate, but it could also unfortunately increase switching losses, acoustic noise and level of interference (EMI) to other equipment, improving

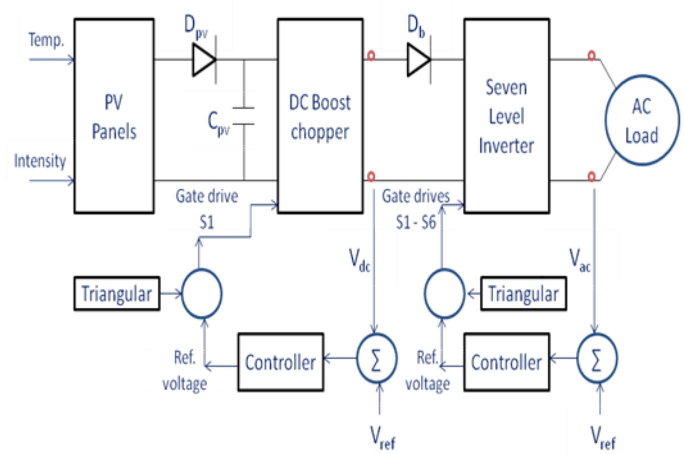


Fig.1. Basic block diagram of single-phase seven-level inverter for stand-alone PV system

its output waveform reduces its harmonic content, EMI generated by the inverter's switching operation and hence, also the size of the filter used. Multilevel inverters have nearly sinusoidal output voltage, output current with better harmonic profile, less stressing of electronic components, less switching losses, smaller filter size and lower EMI than those of conventional two-level inverters. This makes these inverters cheaper, lighter and more compact [15]. The basic block diagram and the circuit diagram of the single phase seven-level inverter for stand-alone PV system are shown in Fig.1 and Fig.2 respectively.

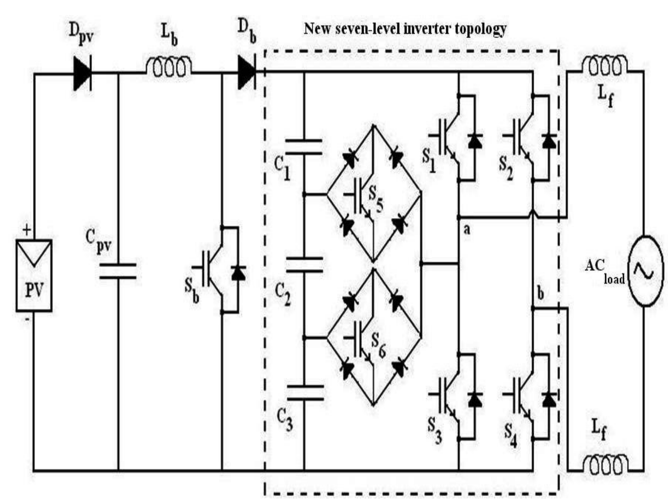


Fig.2. Basic circuit diagram of single phase seven-level inverter for stand-alone PV system

II. NEW MULTI-LEVEL INVERTER TOPOLOGY

This paper uses the development of a modified H-bridge single-phase multilevel inverter which is significantly advantageous over other topologies i.e., less switches and capacitors for inverters of the same number of levels. It comprises of a single phase conventional H-bridge inverter, two diode embedded bidirectional switches and capacitor voltage divider.

A variable dc voltage is generated from the PV array by the variation in temperature and intensity, which is boosted up and made as a constant dc voltage by adjusting the duty ratio of the DC boost chopper. As the loading conditions vary, modulation index is adjusted to compensate the drop in the output voltage. PWM technique is used to generate triggering signals for the DC boost chopper and the inverter switches. High DC bus voltages are necessary to ensure the power flow is from the PV arrays to the load connected. A filtering inductance L_f is used to filter the current injected to the load.

Proper switching of the inverter can produce seven output-voltage levels (V_{dc}, $2V_{dc}/3$, $V_{dc}/3$, 0, $-V_{dc}/3$, $-2V_{dc}/3$ & $-V_{dc}$) from the DC bus voltage.

TABLE I

SWITCHING PATTERN TO ACHIEVE SEVEN-LEVEL OUTPUT VOLTAGE

V_o	S_1	S_2	S_3	S_4	S_5	S_6
V	On	Off	Off	On	Off	Off
2V /3	Off	Off	Off	On	On	Off
V /3	Off	Off	Off	On	Off	On
0	Off	Off	On	On	Off	Off
0*	On	On	Off	Off	Off	Off
-V /3	Off	On	Off	Off	On	Off
-2V /3	Off	On	Off	Off	Off	On
-V	Off	On	On	Off	Off	Off

Table I shows the switching combinations that generates the seven-output voltage levels (V_{dc}, $2V_{dc}/3$, $V_{dc}/3$, 0, $-V_{dc}/3$, $-2V_{dc}/3$ & $-V_{dc}$)

III. PULSE WIDTH MODULATION TECHNIQUE

PWM Technique is used to generate the switching signals. Three reference signals (V_{ref1}, V_{ref2}, and V_{ref3}) were compared with a carrier signal (V_{carr}). The reference signals had the same frequency and amplitude and were in phase with an offset value that was equivalent to the amplitude of the carrier signal. The reference signals were each compared with the carrier signal. If V_{ref1} exceeds the peak amplitude of V_{carr}, V_{ref2} will be compared with V_{carr} until it exceeds the peak amplitude of Vcarr. Then, onward, V_{ref3} would take charge and would be compared with V_{carr} until it reached zero. Once V_{ref3} has reached zero, V_{ref2} would be compared until it reached zero. Then, onward, V_{ref1} would be compared with V_{carr}. Fig.3 shows the resulting switching pattern. Switches S_1, S_3, S_5 and S_6 would be switching at the rate of the carrier signal frequency (1000Hz), whereas S_2 and S_4 would operate at a frequency that is equivalent to the fundamental frequency (50Hz).

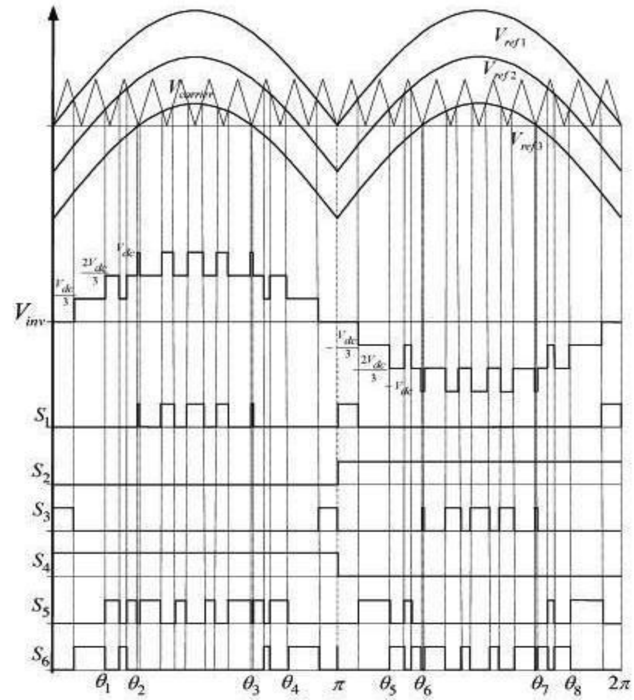


Fig.3: PWM firing pulses for seven-level inverter

For one cycle of the fundamental frequency, the inverter is operated through six modes as in Fig.3. The six modes are described as follows:

Mode 1: $0 < \omega t < \theta_1$ and $\theta_4 < \omega t <$ л

Mode 2: $\theta_1 < \omega t < \theta_2$ and $\theta_3 < \omega t < \theta4$

Mode 3: $\theta_2 < \omega t < \theta_3$

Mode 4: л $< \omega t < \theta_5$ and $\theta_8 < \omega t < 2$л

Mode 5: $\theta_5 < \omega t < \theta_6$ and $\theta_7 < \omega t < \theta_8$

Mode 6: $\theta_6 < \omega t < \theta_7$ (1)

The phase angle depends on modulation index (MI). Theoretically, for a three reference signal and a single carrier signal, the modulation index is defined to be

$$M_a = \frac{A_m}{3A_c} \tag{2}$$

Where,

A_m = Peak value of voltage reference signal

A_c = Peak to peak value of carrier signal

For Ma that is equal to, or less than, 0.33, only the lower reference wave (V_{ref3}) is compared with the triangular carrier signal. The inverter's behavior is similar to that of a conventional full-bridge three-level PWM inverter. However, if Ma is more than 0.33 and less than 0.66, only V_{ref2} and Vref3 reference signals are compared with the triangular carrier wave. The output voltage consists of five dc-voltage levels. The modulation index is set to be more than 0.66 for seven levels of output voltage to be produced. Three reference signals have to be compared with the triangular carrier signal to produce switching signals to the switches.

IV. CONTROL SYSTEM

As Fig.1 shows, the PV inverter system comprises a DC bus voltage controller and output voltage controller. The two main tasks of the control system are maintain constant energy transferred from the PV arrays to the loads and generation of a sinusoidal current with minimum harmonic distortion, also under the presence of output voltage harmonics.

In this paper, conventional PID controller is used to maintain the DC bus voltage constant by comparing V_{dc} and V_{dcref} and feeding the error into the PID controller, which subsequently tries to reduce the error. The DC bus voltage is maintained greater than √2 times the output voltage of the inverter. As the V_{dc} is controlled in the DC-AC seven-level PWM inverter, the change of the duty cycle changes the voltage at the output of the PV arrays.

Also to maintain the V_{ac} constant, when the load changes, another PID controller is used by comparing V_{ac} and V_{acref}. The amplitudes of three reference waveforms of the PWM firing scheme is adjusted, this in-turn adjust the modulation index.

V. SIMULATION RESULTS

The PV system, DC/DC boost converter and the new seven-level inverter topology are simulated using MATLAB/ SIMULINK with the parameters given in Table II. The simulation results of the models are studied individually and the overall system performance for varying solar intensities, duty ratio, modulation index and load are observed.

TABLE II
SPECIFICATIONS FOR 3KVA PV GENERATING SYSTEM

Parameter	Values
80W Solar Panel @ 25°C & 100mW/cm²	
Model No.	NES36-5-80M
Max. output voltage	18.02V
Max. output current	4.44A
Output power	80W
Open circuit voltage	21.9V
Short circuit current	5.20A
Efficiency	13.9%
DC/DC boost converter	
Input voltage	150V
Output voltage	300V
Duty ratio	0.37
Switching frequency	1000Hz
Inductance	63mH
Capacitance	>1.13mF
Inverter	
Output type	Single Phase
Rating	3KVA
DC input voltage	>150V
Output voltage	230V±2%
Output current	10.8A
Power factor	>0.85
Power output	>2500W
Frequency	50Hz±0.1%
Waveform	Sine
Harmonic Distortion	<3% THD for linear load

A. Firing pulse generation and effect of modulation index

The firing pulses are generated for inverter using pulse width modulation technique. The switching pattern for seven-level inverter topology is shown below in Fig.4. Three reference signals (Vref1, Vref2, and Vref3) were compared with a carrier signal (Vcarr).

It is also observed that the change in modulation index will affect the output voltage of the inverter. The variation of output voltage for different modulation index i.e. their corresponding voltage waveforms are shown in Table III and Fig. 5. In this paper, modulation index above 0.66 is only considered to achieve seven-level output voltage of the inverter. It is also noted that, equal voltages of $V_{dc}/3$ are maintained across the voltage divider capacitors.

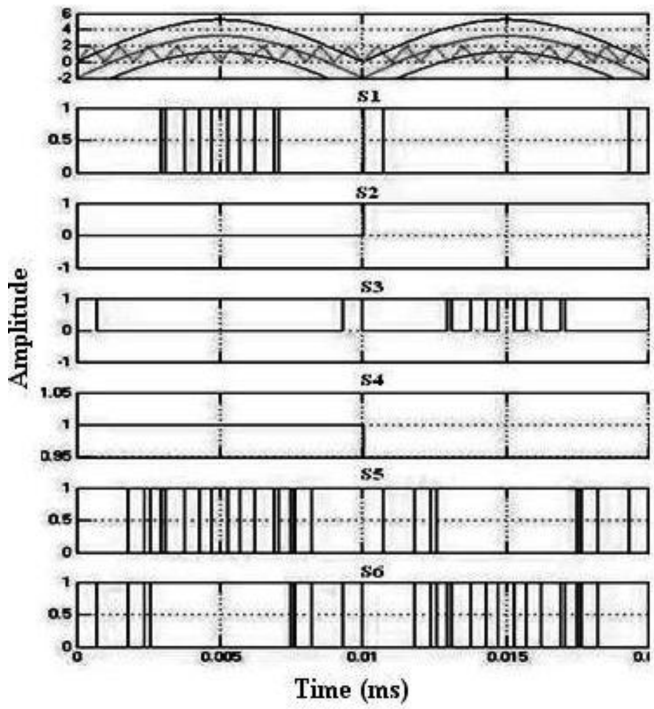
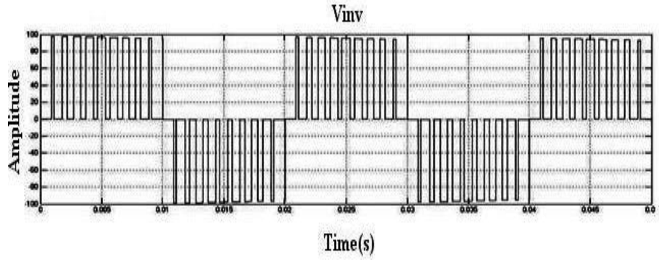


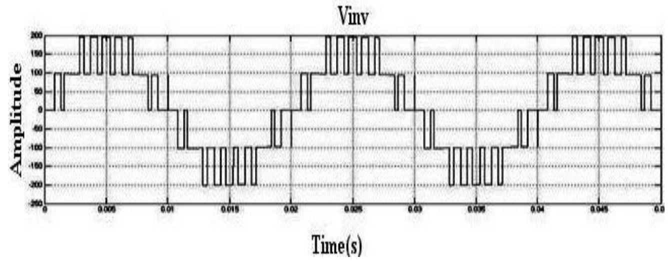
Fig.4 Switching pattern for seven-level inverter

TABLE III
VARIATION OF VOLTAGE LEVELS FOR DIFFERENT MODULATION INDICES

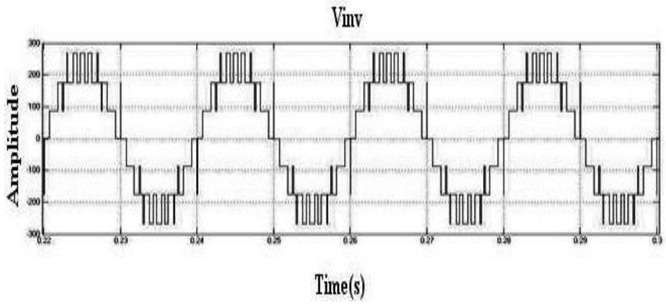
Modulation Index	No. of output voltage levels
0.22	Three level
0.3	
0.33	
0.44	Five level
0.5	
0.6	
0.66	
0.7	Seven level
0.87	
0.92	
0.96	



when 0<Ma<0.33 (V_{dc},.0 & -V_{dc})



when 0.33<Ma<0.66 (V_{dc}, $V_{dc}/2$, 0, -$V_{dc}/2$ & -V_{dc})



when 0.33<Ma<0.99(V_{dc}, $2V_{dc}/3$, $V_{dc}/3$, 0, -$V_{dc}/3$, $2V_{dc}/3$, & -V_{dc})

Fig.5 Output Voltage waveform w.r.t modulation index

B. Performance Analysis of integrated PV system

The overall performance of the stand-alone PV system is investigated for different intensities, duty ratio and modulation indices. Table IV (a), (b) and (c) shows the variation of the output with various intensities, duty ratio and modulation index.

TABLE IV (a)
OUTPUT OF PV INVERTER FOR VARYING INTENSITIES
(at duty ratio = 0.5, modulation index = 0.8 & load =20Ω)

Intensity	PV output voltage	Chopper output voltage	Inverter output voltage	Inverter output current	Inverter output power
100	150.2	294.4	253.7	12.69	91
90	149.2	290.3	251.53	12.6	88
80	148	287.3	249.9	12.5	83
70	146.7	284.6	247.6	12.38	79
60	145.1	281.2	244.9	12.24	75
50	143.1	276.4	241.5	12.08	69.5
40	140.6	272.1	237.2	11.86	63.25
30	137.1	261.4	231.2	11.56	55.3
20	131.2	249.3	221.1	11.05	49.5

TABLE IV (b)
OUTPUT OF PV INVERTER FOR VARYING DUTY RATIOS
(at Intensity = 100mW/cm^2, modulation index = 0.8 & load =20Ω)

Duty Ratio	Chopper output voltage	Inverter output voltage	Inverter output current	Inverter output power
0.25	200	164.5	8.224	39
0.3	216	176.1	8.806	45
0.35	232	187.8	9.392	52
0.4	254	197.2	9.86	59
0.45	263	210.8	10.54	67
0.5	294.3	253.7	12.94	89.6
0.6	336.4	272.6	17.9	98
0.7	372	280.4	21.3	134

TABLE IV (c)
OUTPUT OF PV INVERTER FOR VARYING MODULATION INDICES
(at Intensity = 100mW/cm^2, duty ratio = 0.5 & load =20Ω)

Modulation Index	Inverter output voltage	Inverter output current	Inverter output power
0.708	196.8	9.838	52
0.75	207	10.35	85
0.8	226.6	11.33	63
0.82	227.3	11.37	69
0.875	253.7	12.69	76
0.88	256.6	12.63	82
0.916	267.1	13.35	89

C. Performance of DC/DC boost converter

Fig. 6(a) and 6 (b) shows the output waveforms of PV array and boost converter respectively at fixed temperature, intensity and duty ratio.

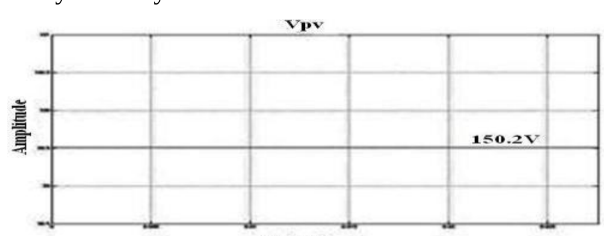


Fig. 6 (a) Output voltage of PV with fixed Temperature=25°C and Intensity=100mW/cm^2

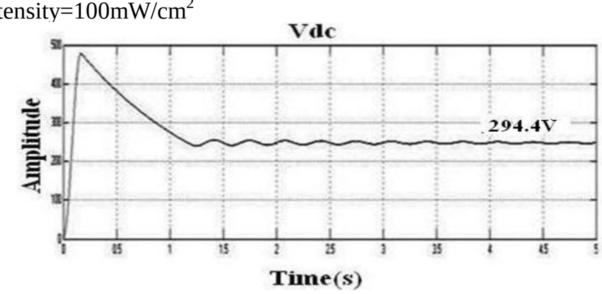


Fig.6 (b) Boosted output voltage at fixed duty ratio=0.5, Temperature=25°C and Intensity=100mW/cm^2

D. Optimum duty ratios and modulation indices

The DC bus voltage output is to be maintained constant at varying intensity by adjusting the duty ratio. As the intensity varies, corresponding duty ratio is to be kept as shown in Table V (a). Also the respective modulation index to be fixed as shown in Table V (b) to maintain constant voltage at varying load.

TABLE V (a)
OPTIMUM DUTY RATIO FOR DIFFERENT INTENSITY TO MAINTAIN 270V DC BUS VOLTAGE

Intensity in mW/cm^2	PV output voltage	Duty Ratio
100	149.3	0.4
95	148.7	0.43
90	148.1	0.45
85	147.5	0.47
80	146.8	0.48
75	146.0	0.49
70	145.2	0.5
65	144.3	0.51
60	143.2	0.52
55	142.1	0.526
50	140.8	0.53
45	139.2	0.54
40	137.3	0.56
35	135.0	0.58
30	131.7	0.61
25	126.4	0.67
20	111.9	0.72
19	95.96	0.76
18	---	---

TABLE V (b)
OPTIMUM MODULATION INDEX FOR DIFFERENT LOADS TO MAINTAIN 230V AC OUTPUT

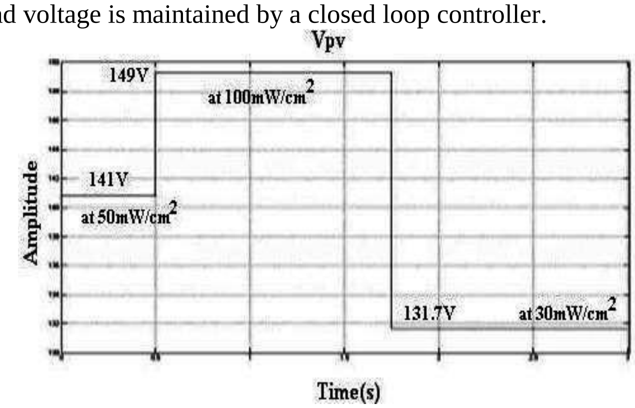
Resistive load in ohms	Duty Ratio
18	0.69
20	0.75
21	0.80
22	0.81
24	0.83
25	0.87
26	0.89
27	0.91
30	0.95

As the load changes, a voltage drop in the output of the inverter is experienced. To compensate this drop in voltage the corresponding modulation index to be varied.

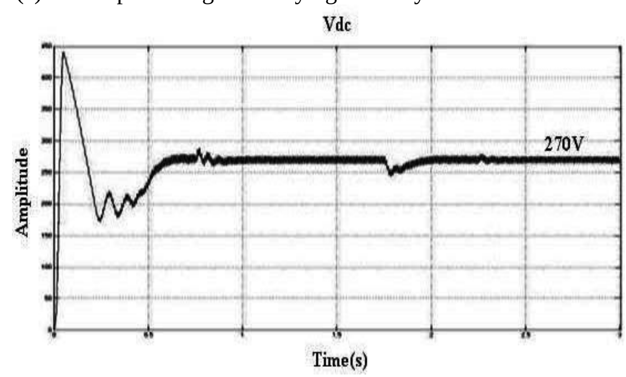
It is observed that output of the PV and DC/DC boost converter varies with intensities when their duty ratio and modulation index are fixed. These variations can be eliminated and maintained constant by adjusting the duty ratio of the boost converter with the help of close loop controllers.

E. Stand-alone PV system with closed loop controller

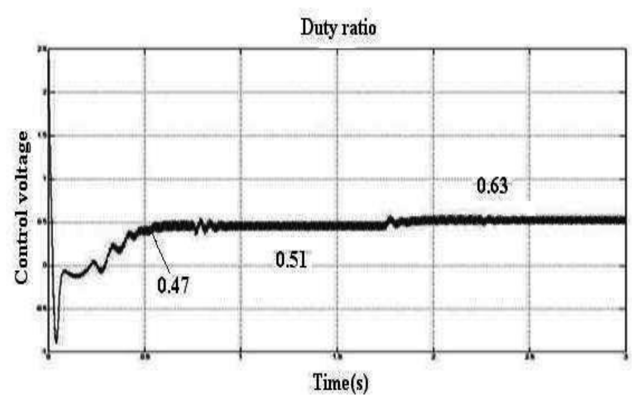
The simulated results of the integrated PV seven-level inverter system with closed loop controller are shown in Fig. 8. for change in intensity of 50mW/Cm^2, 100mW/Cm^2 and 30mW/Cm^2. Depending upon the variation in the intensity, the output voltage varies correspondingly. A closed loop controller is used to adjust the duty ratio of the chopper and the DC bus voltage is maintained constant. Modulation index is also adjusted depending upon the load connected. Constant load voltage is maintained by a closed loop controller.



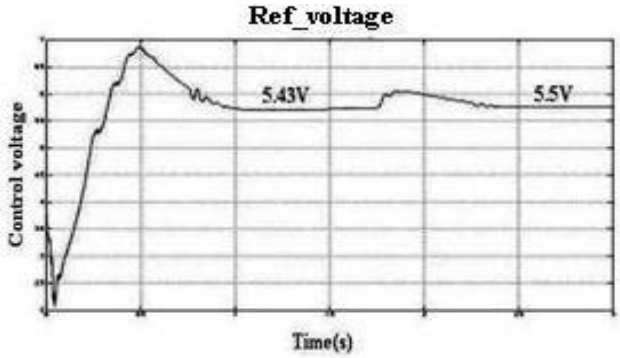
(a) PV output voltage for varying intensity



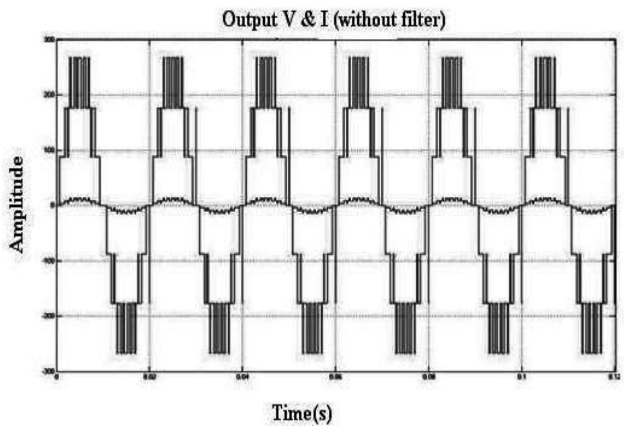
(b) DC bus voltage



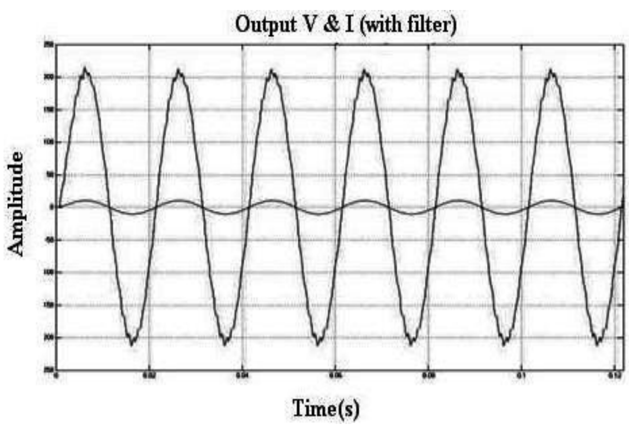
(c) Variation of duty ratio for varying intensities



(d) Variation of reference voltage for varying loads



(e) Inverter o/p waveforms without filter



(f) Inverter o/p waveforms with filter

Fig. 7. Output waveforms of seven-level PV inverter at varying intensities (50mW/Cm^2, 100mW/Cm^2 and 30mW/Cm^2)

VI. CONCLUSION

Simulink model of the stand-alone PV system with new seven level inverter topology with reduced number of switches is developed proving that the multilevel inverters can offer improved output waveforms with lower THD. A 3KVA PV inverter is simulated using MATLAB/SIMULINK. Simple PWM technique is used to generate firing pulses for the inverter switches. It uses three reference signals and a carrier signal to generate PWM switching pulses. The behavior of the new multi-level inverter is analyzed. The detailed analysis of the system performance is carried out for varying solar intensities and loading conditions. The duty ratio of the DC/DC boost converter is adjusted to maintain the DC bus voltage constant for different intensities. By controlling the modulation index, the desired number of levels of the inverter output voltage can be achieved. The effect of modulation index on the output voltage of the PV inverter at different loading conditions is studied and the results are presented.

A closed loop controller is designed to automatically vary the duty ratio and the modulation index. The duty ratios for various intensities are tabulated to maintain constant DC bus voltage. Also the modulation indices, for different load are tabulated to maintain constant load voltage. The variation of duty ratio and modulation index for different intensities and the simulation results of the PV inverter system are discussed and the results are presented.

VII. REFERENCES

1) M. Calais and V. G. Agelidis, “Multilevel converters for single-phase grid connected photovoltaic systems—An overview,” in *Proc. IEEE Int. Symp. Ind. Electron.*, 1998, vol. 1, pp. 224–229.
2) J. Rodríguez, J. S. Lai, and F. Z. Peng, “Multilevel inverters: A survey of Topologies, Controls, and Applications,” IEEE Trans. Ind. Electron.,vol. 49, no. 4, pp. 724–738, Aug. 2002.
3) Nasrudin A.Rahim, Krismadinata Chaniago and Jeyraj Selvaraj,”Single Phase Seven Level Grid-Connected Inverter for Photovoltaic System”,IEEE Trans. Ind. Electron., vol.56,no.6,June 2011.
4) N. A. Rahim and J. Selvaraj, “Multi-string five-level inverter with novel PWM control scheme for PV application,” IEEE Trans. Ind. Electron.,vol. 57, no. 6, pp. 2111–2121, Jun. 2010.
5) Y. Cheng, C. Qian, M. L. Crow, S. Pekarek, and S. Atcitty, “A comparison of diode-clamped and cascaded multilevel converters for a STATCOM with energy storage,” *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1512–1521, Oct. 2006.
6) J. Rodriguez, S. Bernet, B. Wu, J. O. Pontt, and S. Kouro, “Multilevel voltage-source-converter topologies for industrial medium-voltage drives,” *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 2930–2945, Dec. 2007.
7) M. M. Renge and H. M. Suryawanshi, “Five-level diode clamped inverter to eliminate common mode voltage and reduce dv/dt in medium voltage rating induction motor drives,” *IEEE Trans. Power Electron.*, vol. 23, no. 4, pp. 1598–1160, Jul. 2008.
8) E. Ozdemir, S. Ozdemir, and L. M. Tolbert, “Fundamental-frequencymodulated six-level diode-clamped multilevel inverter for three-phase stand-alone photovoltaic system,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 11, pp. 4407–4415, Nov. 2009.
9) M. F. Escalante, J.-C. Vannier, and A. Arzandé, “Flying capacitor multilevel inverters and DTC motor drive applications,” *IEEE Trans. Ind. Electron.*, vol. 49, no. 4, pp. 809–815, Aug. 2002.
10) J. Huang and K. A. Corzine, “Extended operation of flying capacitor multilevel inverter,” *IEEE Trans. Power Electron.*, vol. 21, no. 1, pp. 140–147, Jan. 2006.
11) F. Z. Peng, “A generalized multilevel inverter topology with self-voltage balancing,” *IEEE Trans. Ind. Appl.*, vol. 37, no. 2, pp. 611–617, Mar./Apr. 2001.
12) K. A. Corzine, M. W. Wielebski, F. Z. Peng, and J. Wang, “Control of cascaded multilevel inverters,” *IEEE Trans. Power Electron.*, vol. 19, no. 3, pp. 732–738, May 2004.
13) C. Cecati, F. Ciancetta, and P. Siano, “A multilevel inverter for photovoltaic systems with fuzzy logic control,” *IEEE Trans. Ind. Electron*, vol. 57, no. 12, pp. 4115–4125, Dec. 2010.
14) V. G. Agelidis, D. M. Baker, W. B. Lawrance, and C. V. Nayar, “A multilevel PWMinverter topology for photovoltaic applications,” in *Proc. IEEE ISIE*, Guimäes, Portugal, 1997, pp. 589–594.
15) P. K. Hinga, T. Ohnishi, and T. Suzuki, “A new PWM inverter for photovoltaic power generation system,” in Conf. Rec. IEEE Power Electron. Spec. Conf., 1994, pp. 391–395.