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Control Performance Evaluation of Solar PV Cells Connected to an AC Grid

Meda Koteswararao And Pappu Pawanputhra
PG Student
Assistant Professor

ABSTRACT: *Maximum power point tracking (MPPT) techniques are employed in photovoltaic (PV) systems to make full utilization of the PV array output power which depends on solar irradiation and ambient temperature. Among all the MPPT strategies, perturbation and observation (P&O) method is widely applied in the MPPT controllers due to their simplicity and easy implementation. Multilevel inverters became more popular in the power conversion systems for high power and power quality demanding applications. Among different topologies of MLIs, Cascaded H-Bridge MLIs are more suitable converters for PV applications since each PV panel can act as a separate DC source for each CHB module. This paper presents a simulation analysis 5-level CHBMLI for PV applications with the SPWM control technique using MATLAB/SIMULINK.*

KEYWORDS: Photo voltaic (PV) cells, multilevel inverter (MLI), SPWM, THD.

INTRODUCTION

The demand for renewable energy has increased significantly over the years because of shortage of fossil fuels and greenhouse effect. Among various types of renewable energy sources, solar energy and wind energy have become very popular and demanding due to modern technology world. PV sources are used today in many advantages such as free from pollution. Solar-electric-energy demand has grown consistently by 20% - 25% per annum over the past 20 years, which is mainly due to the decreasing costs and prices [1]. The output power of PV arrays is always changing with weather conditions, i.e., solar irradiation and atmospheric temperature. Therefore, a MPPT control to extract maximum power from the PV arrays at real time becomes indispensable in PV generation system. In recent years, a large number of techniques have been proposed for tracking the maximum power point (MPP) [1-7]. Perturbation and observation (P&O) is widely applied in the MPPT controllers due to their simplicity and easy Implementation [2-3]. P&O method involves a perturbation in the operating voltage of the PV array, while hill climbing strategy introduces a perturbation in the duty ratio of the power converter [2] and is more attractive duty to the simplified control structure [4]. However, the steady state oscillations still exist and the Algorithm is a little more complicated comparing with P&O/hill climbing strategy.

Basically the output of the PV cell is DC form. For commercial purpose it needs to convert to AC form because most of the loads are AC loads. Different topologies MLIs for the conversion from DC to AC are available such as Neutral point clamped MLI (NPC-MLI), Flying capacitor MLI (FC-MLI), Cascade H-Bridge MLI (CHB-MLI) and Asymmetrical Cascade H-Bridge Multilevel inverters. Among them CHB-MLIs are mostly used for PV applications because each cell of CHB-MLI requires separate DC sources which can be easily supplied by individual PV arrays and each H-Bridge cell will be available in a single module. The number of levels of the output wave form increased by cascading the no. of H-Bridge cells. There is a large no. of control techniques developed so far to control the operation of multilevel inverters such as SVPWM, SPWM, OHPWM, SHE-PWM, Hybrid modulation. In these techniques SPWM is the easy to increase the no. of levels in the output waveform with lower harmonic content. In SPWM control technique the gate pulses generated by comparing the sinusoidal reference waveform with the Triangular carrier waveforms. This paper presents the simulation results of a 5-level CHB-MLI with SPWM control techniques for PV applications.

CONFIGURATION AND MODELING OF THE SYSTEM

A. System Configuration

In solar generation system, many PV cells should be connected in parallel and series to obtain the require load current and Voltage. Since Solar panels have a nonlinear voltage-current characteristic, with a distinct Maximum Power Point (MPP), which depends on the environmental factors i.e., temperature and irradiation and in order to continuously harvest maximum power from the solar panels. They have to operate at their MPP despite the inevitable changes in the environment, a power electronic controller is employed with some method for Maximum Power Point Tracking (MPPT). Basically MPPT controller is DC to DC converter which converts the variable DC Voltage into a fixed DC to exactly match load requirements. MPPT is most effective under following conditions:

• Cold weather, cloudy or hazy days: Normally, PV module works better at cold temperatures and MPPT is utilized to extract maximum power available from them.

• During peak load: MPPT can extract more current and deliver the peak load current requirements. Over the past decades many MPPT techniques have been studied. The three most suitable algorithms for large and medium size photovoltaic (PV) applications are, Hill climbing algorithms (perturb and observe), Incremental conductance and Fuzzy logic control.

The voltage generated at the terminals of a photovoltaic panel can feed directly DC loads through MPPT converter. But for AC loads and grid tie renewable energy resources along with the tracking of Maximum Power Point (MPP) of the modules, Inverters are employed to convert direct current produced by solar panels, into the alternating current at required voltage level and frequency requirements of the load, typically in standalone applications where utility power is not available. In case of grid connected Solar or commonly, renewable energy resources dedicated grid tie inverter is used to control the power flow and as well as grid integration. A solar grid tie inverter is a special type of synchronous inverter that feeds to an existing electrical grid.

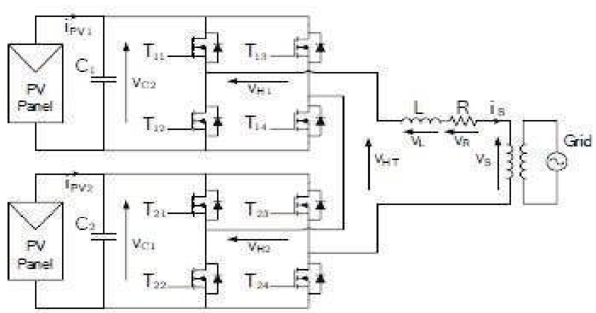

Fig. 1 Topology for grid connection.

B. Mathematical modeling of PV

The photo voltaic cell receives energy from sun and converts the sunlight into dc power the equivalent circuit diagram of a photo voltaic cell is shown in figure.2. The PV cell output voltage is a function of the photo current that mainly determined by load current depending on the solar irradiation level during the operation.

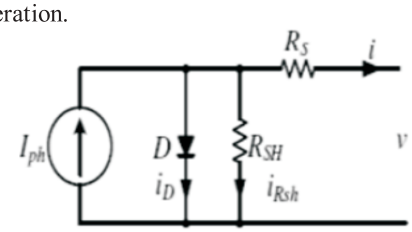

Fig. 2. PV Cell Circuit Model

$$V_{pv} = \left(\frac{N_s A k T}{q}\right) \ln\left(\frac{N_p \times I_{ph} - I_{pv} + N_p \times I_o}{N_p \times I_o}\right) \quad (1)$$

Current output of a pvcell :

$$I_{pv} = N_p \times I_{ph} - N_p \times I_o \left[\exp\left(\frac{q \times (V_{pv} + I_{pv} R_s)}{N_s A k T}\right) - 1\right] \quad (2)$$

$$I_{ph} = [I_{scr} + K_i (T - 298)] \times \frac{\lambda}{1000} \quad (3)$$

The variables terms in above equation are described as shown:

I_{pv}:Output current of a PV cell,
I_o:PV cell saturation current,
I_{ph}:Light generated current in a PVcell,
N_s: Number of modules connected in series
N_p: Number of modules connected in parallel
R_s: The series resistance of cell (0.001 ohm)
A: An ideality factor = 1.6
K:Boltzmann constant=1.3805e-23Nm/K
T: cell temperature in Kelvin=298K
Q: electron charge=1.6e-19 Coulombs
I_{scr} : PV cell short-circuit current at 25°c and1000MW/cm^2
T_r= The reference temperature=301.18k
K_i=Theshort-circuit current temperature coefficient =0.0017A/°C.
Λ=is the PV cell illumination (MW/cm2) =1000Mw/cm2
I_{rr} =Saturation current at T_r= 0.0002
E_{go}= is the band gap for silicon=1.1eV.

Both *k* and *t* have the same temperature unit, either Kelvin or Celsius ,the ideality factor *A* is used to fit the curve to actual characteristic .The voltage obtained from the cell is given by equation (1) it is multiplied by the number of the cells connected in series to calculate the full array voltage .Since the array current is the sum of the current *Ic*is obtained by dividing the array current by the number of cells connected in parallel before being used which is only valid for a certain operating temperature *Tc*with its corresponding solar irradiation level change, the voltage and current outputs of the PV array will follow this change .An increase in solar irradiation causes the output current to increase and the horizontal part of the curve moves upwards increase in cell temperature causes the voltage to move leftward, while decreasing the temperature causes the opposite effect. The V-I curve show how a photovoltaic module responds to all possible different solar irradiation and cell temperature conditions.

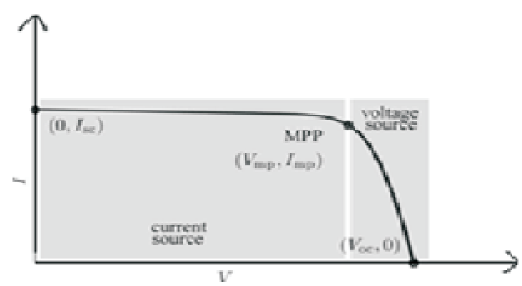

Fig. 3. Maximum Power Point (V_{mp}, I_{mp})

Characteristic *I–V* curve of a practical PV device and the three limiting points: short circuit (0, *I*sc), MPP (*V*mp, *I*mp), and open circuit (*V*oc, 0). The V-I characteristics shown in figure 3 has only one mpp point (Vmp, Imp) where the load operating point must coincide with this so that the load can be delivered maximum power only one load value produces a maximum power .To operate the module at MPP, a dc -dc power electronic converter is accompanied with PV system this converter is nothing but a booster converter which boosts the voltage of PV array available at low voltage to the voltage of load which requires higher voltage.

C. Conventional with Fixed Perturb- P&O

Perturbation and Observation (P&O) can track the Maximum Power Point (MPP) all the time, irrespective of the atmospheric conditions, like temperature and irradiation P&O algorithms are widely used in MPPT because of their simple structure. In this method, a fixed perturb value is utilized to generate a reference signal for the outer control loop this perturb value dependent on the system designer. The algorithm compares periodically perturbation in the operating voltage of the PV array. It can be seen that incrementing (decrementing) the voltage increases (decreases) the power when operating on the left of the MPP.As Shown in figure.3 and decreases (increases) the power when on the right of the MPP. Therefore, if there is an increase in power, the subsequent perturbation should be kept the same to reach the MPP and if there is a decrease in power, the perturbation should be reversed. The flow chart algorithm and implementation block diagram of P&O are show in figure.1 and figure.4 respectively. As a result of previous experience the designer decides the fixed perturb value which is designer dependent. Therefore, the solution the MPPT is utilized to control the power converter. Provided by this method is not generic and system dependent. For small perturb steps, the tracking is slow but the power/voltage oscillations are minimal. In the case of large perturb step, faster tracking is achieved with increased oscillations. Hence, P&O techniques with fixed perturb suffer an inherent tracking–oscillations trade off problem. [6]

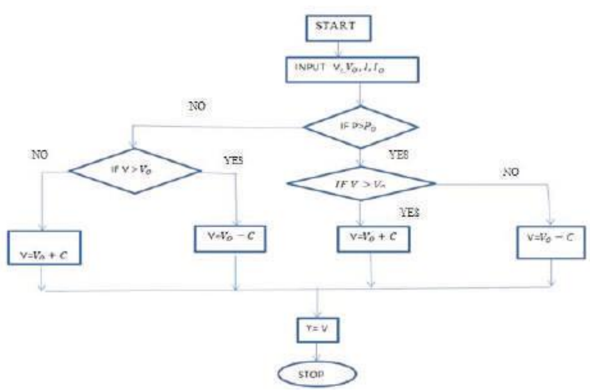

Fig.4.Maximum power point tracking With Perturbation and Observation Flow Chart

Table 1 Perturbation Table

Perturbation	*Change in power*	*Next perturbation*
Positive	*Positive*	*Positive*
Positive	*Negative*	*Negative*
Negative	*Positive*	*Negative*
Negative	*Negative*	*Positive*

D. Modeling of Power Converters

Since the switching frequencies for the three converters are all set as 50*Hz*, time-average models are developed for the converters by not considering the high frequency harmonics.

1) Boost converter

The boost converter is used to couple different voltage levels between the dc link and the terminal output of solar panel, moreover, it can make the solar panel operating at maximum power point under any environmental condition. The equations can be described as follow, and the symbols here are set in accordance with Fig.1.

$$V_{in} - V_T = L_1 \cdot di_1/dt + R_1 i_1 \quad (4)$$
$$V_T = V_d.(1 - d_1) \quad (5)$$

Where VinandVdare the solar panel output voltage and dc link voltage respectively, *VT* is the voltage across switch ST, *d1* is the duty ratio of the switch. Time average model of the boost converter can be established using the average switching method. The perturbation and observation method is preferred in this system due to its simplicity and robustness to the variations of model parameters. More details about this MPPT method is well described in [8] and will not be focused in this paper. The reference value of the solar panel terminal voltage is determined by the MPPT algorithm and the control system is used to track the reference. Dual-loop control strategy is chosen for the boost converter, where the output of the outer voltage loop is set as the reference value for the inner current control loop which is shown in Fig.5. A detail block diagram

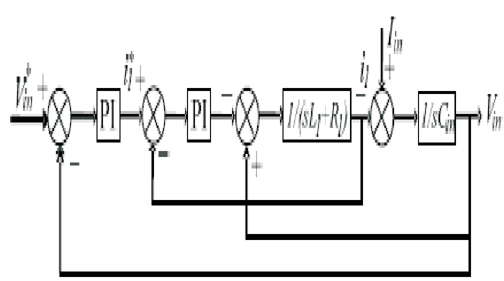

Fig .5.control block diagram of boost converter

2) Single-phase inverter

The inverter is the main power supply for the local ac load. It is a second-order system with two inputs (dc voltage *Vd*and load current *i0*) and can be expressed as below:

$$C_f \frac{dv_c}{dt} = i_2 - i_0 \quad (6)$$
$$L_f \frac{di_2}{dt} = u_{ab} - v_c - R_f.i_2 \quad (7)$$

The state-space equations can be written as follow by taking the inductor current *i2* and capacitor voltage *vc*as the state variables.

$$\frac{d}{dt}\begin{bmatrix} i_2 \\ v_C \end{bmatrix} = \begin{bmatrix} -\frac{R_2}{L_2} & -\frac{1}{L_2} \\ \frac{1}{C_2} & 0 \end{bmatrix}\begin{bmatrix} i_2 \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L_2} \\ 0 \end{bmatrix} u_{AB} + \begin{bmatrix} 0 \\ -\frac{1}{C_2} \end{bmatrix} i_o \quad (8)$$

Using state-space average model, the terminal voltage *UAB* of the inverter can be represented by the dc-link voltage *Vd*as below:

$u_{AB} = m V_d . \sin \omega t$
*m*is the modulation index of SPWM.

The inverter acts as a voltage source node in the isolated system and needs to provide a stable and high quality output ac voltage. When the load is nonlinear, i.e. a diode rectifier load, the load current is intermittent and contains a great deal of low frequency harmonics, and this current will generate low frequency harmonics voltage across the filtering inductor. If there is no appropriate control scheme, this harmonics voltage will distort the inverter output voltage and this may do harm to some sensitive loads connected to the same ac bus. Repetitive control is very suitable for inverter supplying nonlinear load, but it has a slow dynamic response, when the load changes suddenly, the output voltage of the inverter will take a long time (several to dozens of fundamental periods) to restore. Dual-loop control strategy is chosen for the inverter system, where the output of the instantaneous voltage loop is set as the reference value for the inner current control loop.

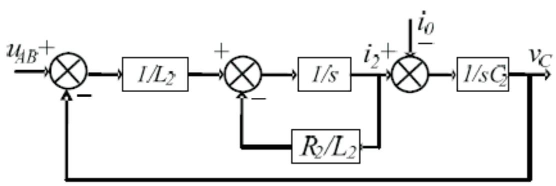

Fig.6. Control block diagram of single phase inverter

3) Cascaded H-Bridge Multilevel inverter

The cascaded multilevel inverter topology consists of *n* H-bridge converters connected in series and is shown in Fig. 7. Each DC link is fed by a short string of PV panels. By different combinations of the four switches in each H bridge, three output voltage levels can be generated, *–vc*, 0,or *+vc*. A cascaded multilevel inverter with *n*input sources will provide *2n+1* levels to synthesize the AC output waveform. This *(2n+1)*-level voltage waveform enables the reduction of harmonics in the generated current, reducing the output filters. The work of multilevel inverter is to synthesize a desired voltage from Several Separate DC Source. Fig.7 shows the basic structure of a SDCS. Each SDCS is connected to an H-bridge inverter. The ac terminal voltages of different level inverters are connected in series. Unlike the diode-clamp or flying capacitor inverter, the cascaded inverter does not require any voltage clamping diodes or voltage balancing capacitors. The numbering order of the switches is S1, S2, S3, S4, S5, S6, S7 and S8.The numbering is immaterial as along as the switches are turned on and off in the right sequence to produce the desired output waveform.

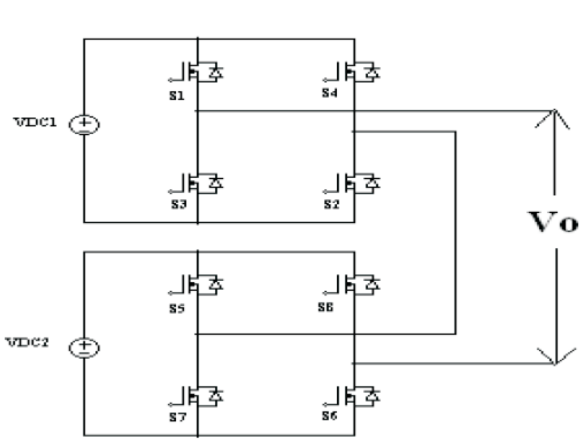

Fig.7. Cascaded H Bridge Inverter

4) Switching patterns of the proposed single phase five-level PWM inverter

There are two PWM methods mainly be used in multilevel inverter control strategy. One is fundamental switching frequency and another one is high switching frequency. High switching frequency can be classified as space vector PWM, selective harmonics elimination PWM and Sinusoidal Pulse Width modulation (SPWM). Among these PWM methods SPWM is the mostly used for multilevel inverter, because it has very simple and easy to implement.

1. For an output voltage level Vo = Vdc, S1 S2 & S5 S6 are turned on.
2. For an output voltage level Vo = Vdc /2, S1 and S2 are turned on.
3. For an output voltage level Vo = 0, all switches are turn off.
4. For an output voltage level Vo = - Vdc /2, S3 and S4 are turned on.
5. For an output voltage level Vo = - Vdc, S3 S4 &S7 S8 are turned on.

Table2 Switching Table for Five -Level Inverter

Output(Vo)	S1	S2	S3	S4	S5	S6	S7	S8
Vo = Vdc	1	1	0	0	1	1	0	0
$V_o = V_{dc}/2$	1	1	0	0	0	0	0	0
Vo = 0	0	0	0	0	0	0	0	0
Vo = -Vdc/2	0	0	1	1	0	0	0	0
Vo = - Vdc	0	0	1	1	0	0	1	1

TOTAL *HARMONIC DISTORTION*

The most widely used measure to indicate the quantity of harmonics contents is the Total Harmonics

Distortion (THD), which is defined in terms of the amplitudes of the harmonics, Hn, at frequency nω0, where ω0 is the frequency of fundamental component whose amplitude of H1 and n is the integer. The THD is mathematically given by [9]

$$THD=\frac{\sqrt{\sum_{n=2}^{\infty} H_n^2}}{H_1}$$

The THD is mathematically given by the system performance of five level inverter and is further improved in terms of the THD for switching frequency of 2 kHz.

FILTER

The filter consists of L-C circuit where inductor L is connected in series with the load and capacitor across the load. It is inserted between the output of the inverter and the load. It is used to remove harmonics where inductor L blocks the dominant harmonics and capacitor C provides an easy path to the n_{th} harmonic ripple current. In practice it has been found that, capacitor provides effective filtering if load consists of R and L in series.[10]

MATLAB/SIMULINKMODEL

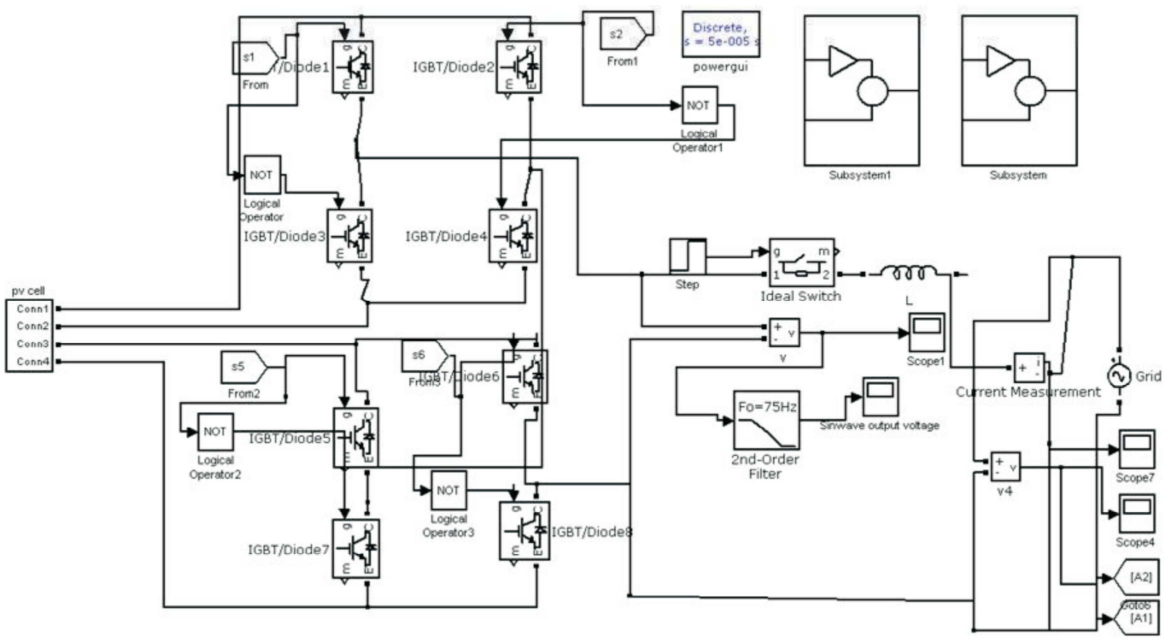

Fig.8. Simulation Diagram for Photovoltaic System using Single Phase Five Level CHBML Inverter connected to Grid

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RESULTS

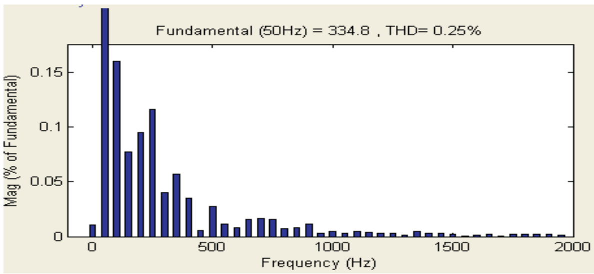

Fig.9.THD of Five level output voltage

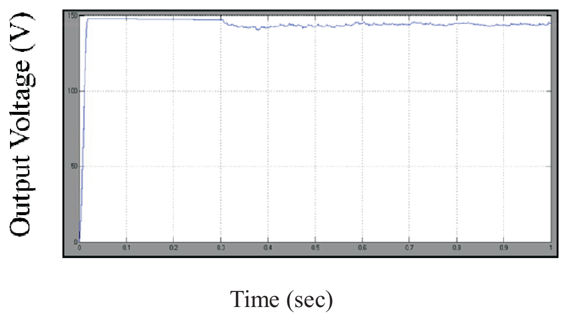

Fig.10. PV cell output voltage

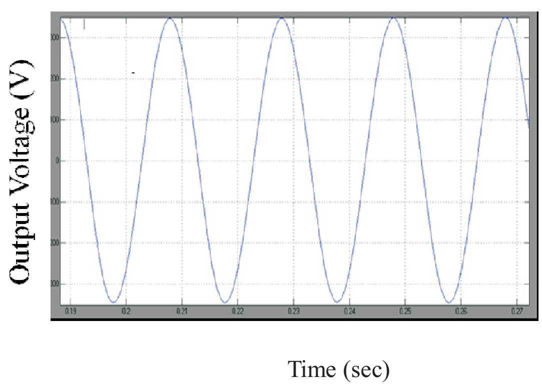

Fig.11. Filtered output Voltage

Table 3 System Parameters

Parameters	**Values**
Dc Capacitor	1000µF
Coupling Inductor	2.2mH
Switching frequency	2KHz
Number of cascaded cells	2
Grid voltage	290V
Frequency	50Hz

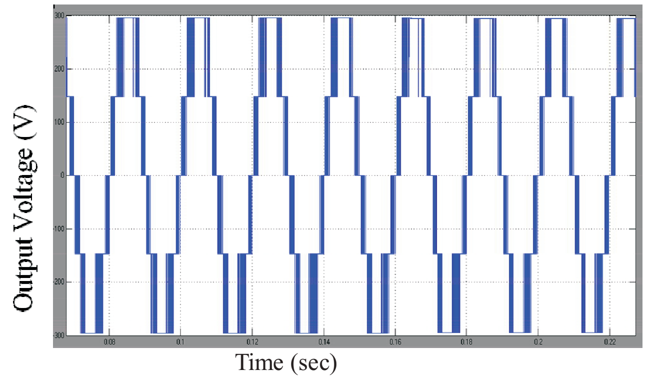

Fig.12.Five level output Voltage

CONCLUSION

In this paper, a cascaded H-bridge multilevel converter has been proposed as a feasible multistring topology for PV applications. The converter features several advantages such as the generation of high-quality currents, the capacity to operate at a lower switching frequency than a three-level converter, and the modularity that can reduce the cost of the solution. The converter is first controlled using a scheme proposed for multilevel inverter and improved by adding MPPT algorithms. A single phase cascaded H-Bridge for grid connected system is proposed. A Matlab/Simulink based model is developed and simulation results are presented.

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BIOGRAPHIES

M. KoteswaraRao was born in july 14th 1988.He graduated in 2011 from Vignan's Lara Institute Of Technology And Science, Guntur, India in Electrical Engineering. He is currently pursing M.TECH. from GVP college of engineering, Visakhapatnam. His area of interest is Renewable Energy and Power Quality.

P. PawanPuthra was born in 15thNov 1983. He graduated in JNTU Hyderabad from St.Theresa Institute of Engg& Tech., Garividi India in the year 2006. He obtained his post graduation from Vellore Institute of Technology (VIT) with Specialization Power Electronics & Drives in year 2008. Presently he is working as an Asst. professor in GVP College of Engineering. His main area of research is Power Electronics & Drives, FACTS, and HVDC TransmissionSystems