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Research Article

Simulation Analysis of PV Based Single Phase Modified H-Bridge Eleven Level Inverter

[1]I. William Christopher and [2]R. Ramesh
[1]Department of Electrical and Electronics Engineering, Tagore Engineering College, Chennai, India
[2]Department of Electrical and Electronics Engineering, College of Engineering Guindy,
Anna University, Chennai, India

Abstract: This study presents the simulation analysis of a PV based single-phase modified H-bridge eleven-level inverter. Multilevel inverters offer high power capability, associated with lower output harmonics and lower turn-off losses. This study informs a PV based multilevel inverter using a H-bridge output stage with four bidirectional auxiliary switches. The inverter is capable of producing eleven levels of output-voltage levels ($+V_{dc}/5$, $+2V_{dc}/5$, $+3V_{dc}/5$, $+4V_{dc}/5$, $+V_{dc}$, '0' level, $-V_{dc}/5$, $-2V_{dc}/5$, $-3V_{dc}/5$, $-4V_{dc}/5$ and $-V_{dc}$) from the DC supply. Theoretical predictions of the proposed PV based single-phase modified H-bridge eleven-level inverter with MPPT are validated using simulation in MATLAB SIMULINK.

Keywords: Maximum Power Point Tracking (MPPT), Modified H-Bridge Eleven-Level Inverter (MHBELI), Photovoltaic (PV) system

INTRODUCTION

Due to the need, constant increase of costs of fossil fuels and its huge negative impact on the environment, renewable energy sources have recommended and developed, in recent years. It is estimated that the electrical energy generation from renewable sources is increased from 19%, in 2010, to 32%, in 2030, because of innovation in power electronics techniques and control strategies (European Commission, 2010). Among various types of renewable energy sources, solar photovoltaic energy is one of the fastest growing and promising, owing to pollution free. In Photovoltaic (PV) systems, solar energy is converted into electrical energy by PV arrays. PV arrays are very popular since they are clean, inexhaustible and require little maintenance. Photovoltaic systems require interfacing power converters like dc-dc converter and dc-ac inverter between the PV arrays and the grid. The generated power from PV system can be distributed to power system networks through grid-connected inverters.

A single-phase grid-connected inverter is usually used for residential or low-power applications of power ranges that are less than 10 kW (Calais and Agelidis, 1998). Types of single-phase grid-connected inverters have been investigated (Kjaer *et al*., 2005). A well-known topology of this inverter is full-bridge three-level. Multilevel inverters are promising; they have nearly sinusoidal output-voltage waveforms, output current with better harmonic profile, less stressing of electronic components due to reduced voltages, switching losses that are lower than those of conventional two-level inverters, a smaller filter size and lower EMI, all of which make them cheaper, lighter and more condensed (Hinga *et al*., 1994; Cheng *et al*., 2006).

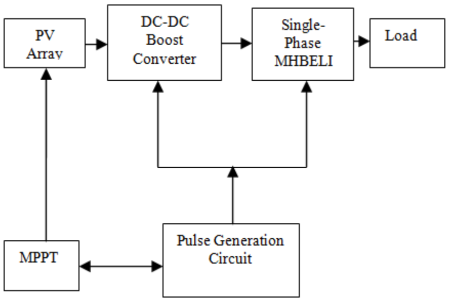

Fig. 1: Single-phase MHBELI for PV system

Over the years, different types of multilevel inverter topologies have been introduced. Familiar ones are diode-clamped, flying capacitor or capacitor clamped, cascaded H-bridge and simplified H-bridge multilevel inverters (Rodriguez *et al*., 2002; Ceglia *et al*., 2006). This study illustrates the development of a single-phase modified H-bridge eleven-level inverter that has four bidirectional switches with embedded diodes. The proposed single-phase MHBELI for PV system is shown in Fig. 1.

Photovoltaic (PV) arrays were attached to the inverter via a dc-dc boost converter. The power

Corresponding Author: I. William Christopher, Department of Electrical and Electronics Engineering, Tagore Engineering College, Chennai, India

generated by the inverter is to be delivered to the power set-up, so the utility grid, rather than a load, was used.

The dc-dc boost converter was required because the PV arrays had a voltage that was lower than the grid voltage. High dc bus voltages are necessary to ensure that power flows from the PV arrays to the load. The inverter used in the power stage offers a significant enhancement in terms of lower component count and condensed design complexity when compared with the other existing eleven-level inverters.

METHODOLOGY

PV array with MPPT:

PV array: A solar PV system is powered by many crystalline or thin film PV modules. Individual PV cells are interconnected to form a PV module. This takes the form of a panel for easy installation. PV cells are made of light-sensitive semiconductor materials that use photons to dislodge electrons to drive an electric current.

A PV cell basically is a p-n semiconductor junction. When exposed to the light, a DC current is generated. The generated current varies linearly with the solar irradiance. The equivalent electrical circuit of a practical PV cell can be treated as a current source parallel with a diode shown in Fig. 2.

The I-V characteristics of the equivalent circuit of PV can be determined by following equations. The current through diode is given by:

$$I_D = I_o\left[e^{\left(\frac{q(V+IR_s)}{KT}\right)} - 1\right] \tag{1}$$

While, the PV cell output current:

$$I = I_{pv} - I_D - I_P \tag{2}$$

$$I = I_{pv} - I_o\left[e^{\left(\frac{q(V+IR_s)}{KT}\right)} - 1\right] - \left[\frac{(V+IR_s)}{R_p}\right] \tag{3}$$

where,

I = PV cell output current (A)
I_{PV} = Light generated current (A) (Short circuit value assuming no series/ shunt resistance)
I_O = Diode saturation current (A)
I_P = Current through parallel resistance
q = Electron charge (1.6×10^{-19} C)
K = Boltzmann constant (1.38×10^{-23} J/K)
T = Cell temperature in Kelvin (K)
V = PV cell output Voltage (V)
R_s = PV cell series resistance (Ω)
R_p = PV cell parallel resistance (Ω)

Incremental conductance MPPT with boost converter: When a PV module is directly coupled to a load, the PV system operating point will be at the intersection of its *I-V* curve and the load line which is the *I-V* relationship of the load. In other words, the impedance of load dictates the operating condition of the system.

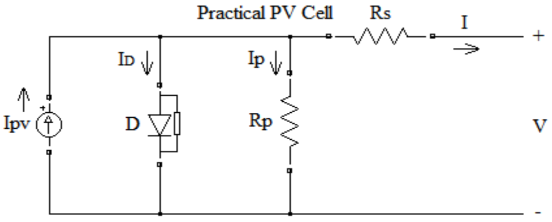

Fig. 2: Equivalent electrical circuit of a PV cell

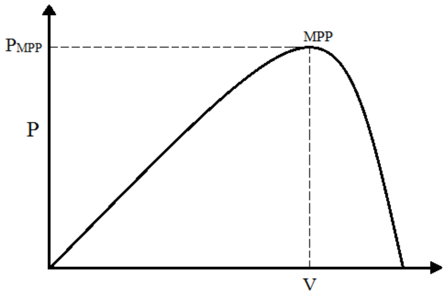

Fig. 3: P-V characteristics of PV cell

In general, this operating point is not often at the PV system Maximum Power Point (MPP), thus it is not producing the maximum power. To avoid this problem, a Maximum Power Point Tracker (MPPT) can be used to maintain the PV system's operating point at the MPP. MPPTs can take out more than 97% of the PV power when properly optimized. The P-V characteristics of the PV cell are illustrated in Fig. 3. It depends on open circuit voltage (V_{oc}), short circuit current (I_{sc}) and maximum power point.

The INC algorithm is widely used due to the high tracking accuracy at steady state and good adaptability to rapidly varying atmospheric condition. The PV module output might change with respect to change in solar radiations. The Incremental Conductance MPPT algorithm was implemented in the dc-dc boost converter to maximize the power. The output of the MPPT is a function of duty cycle, it is nothing but a pulse required for the MOSFET switch of a DC-DC boost converter. By varying the duty ratio between 0.77 and 0.85, the output of the DC-DC converter is step-up or boosted. The boosted DC voltage is given as an input to the single-phase MHBELI.

Power circuit:

Power circuit advantages: A single-phase MHBELI has the following merits over other existing multilevel inverter topologies:

- It consists of single-phase conventional H-bridge inverter with four bidirectional auxiliary switches and a capacitor voltage divider formed by five capacitors
- Improved output waveforms
- Lower Electromagnetic Interference (EMI) and Total Harmonic Distortion (THD)
- Attains 60% drop in the number of main power switches required

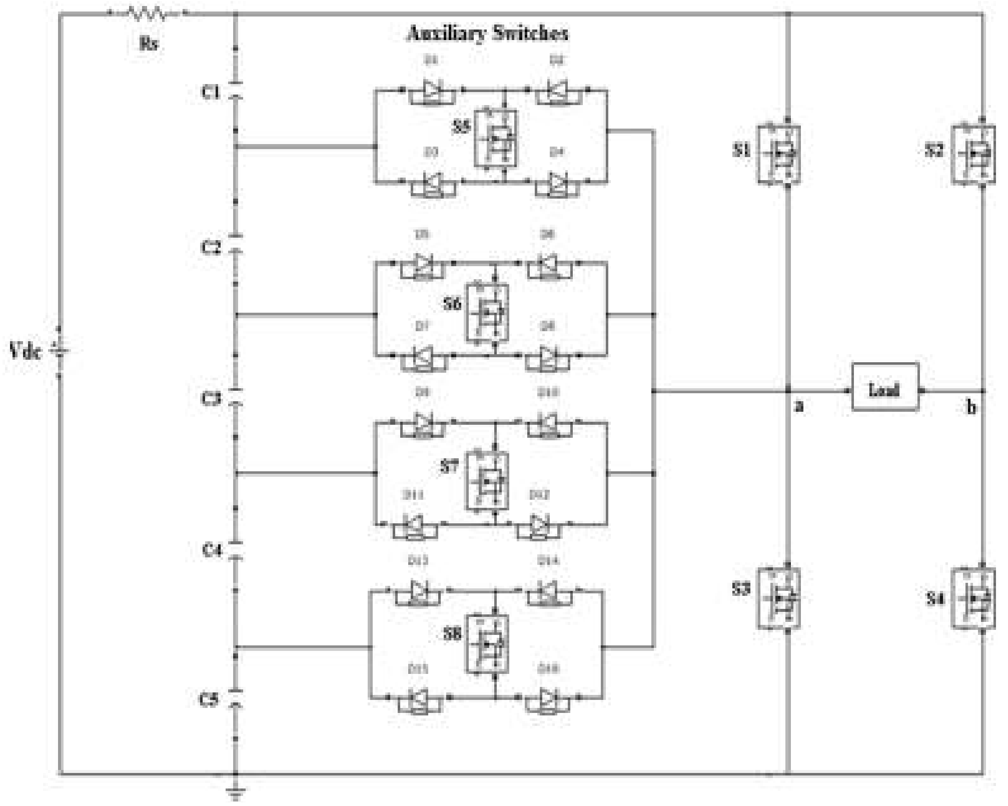

Fig. 4: Single-phase MHBELI circuit

Moreover, since the capacitors are connected in parallel with the main dc power supply, no significant capacitor voltage swing is produced during normal operation, avoiding a problem that can limit operating range in some other multilevel configurations.

Power circuit description: The proposed single-phase Modified H-Bridge Eleven-Level Inverter (MHBELI) was developed from the five-level inverter reported in (Ceglia *et al*., 2006; William and Ramesh, 2012). It includes (Christopher *et al*., 2012; Rahim *et al*., 2011), a single-phase conventional H-bridge inverter which has four main switches S1, S2, S3 and S4, a capacitor voltage divider formed by five capacitors C_1, C_2, C_3, C_4 and C_5, as shown in Fig. 4.

The bidirectional auxiliary switches, formed by the controlled switches S5, S6, S7 and S8 and with sixteen diodes, D_1 to D_{16}. The proposed single-phase MHBELI power circuit for PV system with four bidirectional auxiliary switches is shown in Fig. 4. Proper switching of the inverter can produce eleven output-voltage levels ($+V_{dc}/5$, $+2V_{dc}/5$, $+3V_{dc}/5$, $+4V_{dc}/5$, $+V_{dc}$, '0', $-V_{dc}/5$, $-2V_{dc}/5$, $-3V_{dc}/5$, $-4V_{dc}/5$ and $-V_{dc}$) from the PV system.

The modified H-bridge multilevel inverter topology is obviously cost-effective compare to other topologies, i.e., it requires less number of power switches, power diodes and less capacitor for inverters of the same number of levels.

POWER CIRCUIT OPERATION

The single-phase MHBELI is capable of producing eleven levels of output-voltage levels ($+V_{dc}/5$, $+2V_{dc}/5$, $+3V_{dc}/5$, $+4V_{dc}/5$, $V_{dc}/5$, 0, $-V_{dc}/5$, $-2V_{dc}/5$, $-3V_{dc}/5$, $-4V_{dc}/5$ and $-V_{dc}$) from the PV system, shown in Fig. 5 and it can be easily understood by the Table 1.

Mode I operation: The switch S1 is ON, connecting the load positive terminal to *V*dc and S4 is ON, connecting the load negative terminal to ground. Remaining switches S2, S3, S5, S6, S7 and S8 are OFF; the voltage across the load terminals *ab* is *Vdc*.

Mode II operation: The bidirectional switch S5 is ON, connecting the load positive terminal and S4 is ON, connecting the load negative terminal to ground. Remaining switches S1, S2, S3, S6, S7 and S8 are OFF; the voltage across the load terminals *ab* is *4Vdc/5*.

Mode III operation: The bidirectional switch S6 is ON, connecting the load positive terminal and S4 is ON, connecting the load negative terminal to ground. Remaining switches S1, S2, S3, S5, S7 and S8 are OFF; the voltage across the load terminals *ab* is 3*Vdc/5*.

Mode IV operation: The bidirectional switch S7 is ON, connecting the load positive terminal and S4 is ON, connecting the load negative terminal to ground.

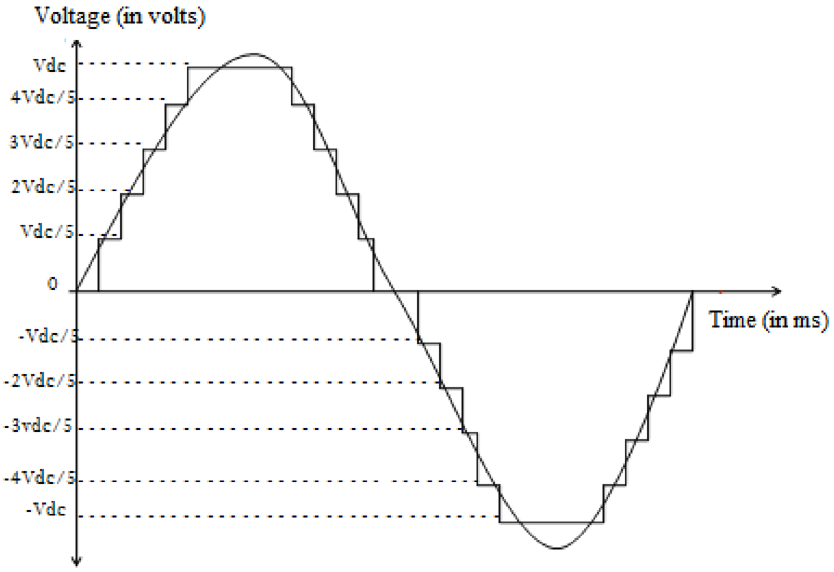

Fig. 5: Output voltage waveform of 1-phase MHBELI

Table 1: Switching combinations required to generate the eleven-level output voltage waveform

Vo	S1	S2	S3	S4	S5	S6	S7	S8
Vdc	1	0	0	1	0	0	0	0
4Vdc/5	0	0	0	1	1	0	0	0
3Vdc/5	0	0	0	1	0	1	0	0
2Vdc/5	0	0	0	1	0	0	1	0
Vdc/5	0	0	0	1	0	0	0	1
0	1	1	0	0	0	0	0	0
0*	0	0	1	1	0	0	0	0
-Vdc/5	0	1	0	0	1	0	0	0
-2Vdc/5	0	1	0	0	0	1	0	0
-3Vdc/5	0	1	0	0	0	0	1	0
-4Vdc/5	0	1	0	0	0	0	0	1
-Vdc	0	1	0	0	0	0	0	0

Remaining switches S1, S2, S3, S5, S6 and S8 are OFF; the voltage across the load terminals *ab* is 2*Vdc*/5.

Mode V operation: The bidirectional switch S8 is ON, connecting the load positive terminal and S4 is ON, connecting the load negative terminal to ground. Remaining switches S1, S2, S3, S5, S6 and S7 are OFF; the voltage across the load terminals *ab* is *Vdc*/5.

Mode VI operation: This mode of operation has two possible switching combinations, Either switches S1 and S2 are ON, remaining switches S3, S4, S5, S6, S7 and S8 are OFF or S3 and S4 are ON, remaining switches S1, S2, S5, S6, S7 and S8 are OFF. In both switching combinations terminal *ab* is short circuited, hence the voltage across the load terminals *ab* is zero.

Mode VII operation: The bidirectional switch S5 is ON, connecting the load positive terminal and S2 is ON, connecting the load negative terminal to *V*dc. Remaining switches S1, S3, S4, S6, S7 and S8 are OFF; the voltage across the load terminals *ab* is -*Vdc*/5.

Mode VIII operation: The bidirectional switch S6 is ON, connecting the load positive terminal and S2 is ON, connecting the load negative terminal to ground. Remaining switches S1, S3, S4, S5, S7 and S8 are OFF; the voltage across the load terminals *ab* is -2*Vdc*/5.

Mode IX operation: The bidirectional switch S7 is ON, connecting the load positive terminal and S2 is ON, connecting the load negative terminal to ground. Remaining switches S1, S3, S4, S5, S6 and S8 are OFF; the voltage across the load terminals *ab* is -3*Vdc/5*.

Mode X operation: The bidirectional switch S8 is ON, connecting the load positive terminal and S2 is ON, connecting the load negative terminal to ground. Remaining switches S1, S3, S4, S5, S6 and S7 are OFF; the voltage across the load terminals *ab* is -4*Vdc*/5.

Mode XI operation: The switch S2 is ON, connecting the load negative terminal to *V*dc and S3 is ON, connecting the load positive terminal to ground. Remaining switches S1, S4, S5, S6, S7 and S8 are OFF; the voltage across the load terminals *ab* is -*Vdc*.

In the eleven-level inverter circuit five capacitors in the capacitive voltage divider are connected directly across the dc supply voltage V_{dc} and since all switching combinations are activated in an output cycle, the dynamic voltage balance between the five capacitors is automatically restored.

SIMULATION RESULTS

Simulation model: The simulation model of single-phase MHBELI for PV system using MPPT is developed using MATLAB SIMULINK tool box, is illustrated in Fig. 6.

This model contains of photovoltaic module, DC-DC boost converter with incremental conductance MPPT algorithm and finally the proposed single-phase MHBELI.

The PWM signal for each of the switching devices in the MHBELI circuit comes from the pulse generator block. This block includes all the PWM signals required for switches are multiplexed on a single bus to the eleven-level inverter power circuit.

PV module characteristic: The simulation of 250 W PV module for the following specifications has been simulated is shown in Table 2.

The simulated V_{oc}-I_{sc} characteristic is shown in Fig. 7. The x-axis represents the open circuit voltage (V_{oc}) of 37.47V and y-axis represents the corresponding short circuit current (I_{sc}) of 8.76A.

The simulated P-V characteristic is shown in Fig. 8. The x-axis represents the open circuit voltage (V_{oc}) of 37.47V and y-axis represents the corresponding maximum output power of 250 W.

Converter: The DC-DC Boost converter input power is taken from PV module and the output of the converter is maximized using Incremental conductance algorithm is fed to the single-phase MHBELI through dc-dc boost converter. The PV module has been tested for load change due to change in solar radiation. The incremental conductance algorithm was implemented in the dc-dc boost converter. The output of the MPPT is the duty-cycle function. As the dc-link voltage *Vdc* was controlled in the dc-ac single-phase MHBELI, the change of the duty cycle changes the voltage at the output of the PV panels.

The incremental conductance method is based on the fact that the slope of the PV array power curve is zero at the MPP, positive on the left of the MPP and negative on the right, as given:

$$\frac{dp}{dv} = 0, \text{ at MPP} \tag{4}$$

$$\frac{dp}{dv} > 0, \text{ left of MPP} \tag{5}$$

$$\frac{dp}{dv} < 0, \text{ right of MPP} \tag{6}$$

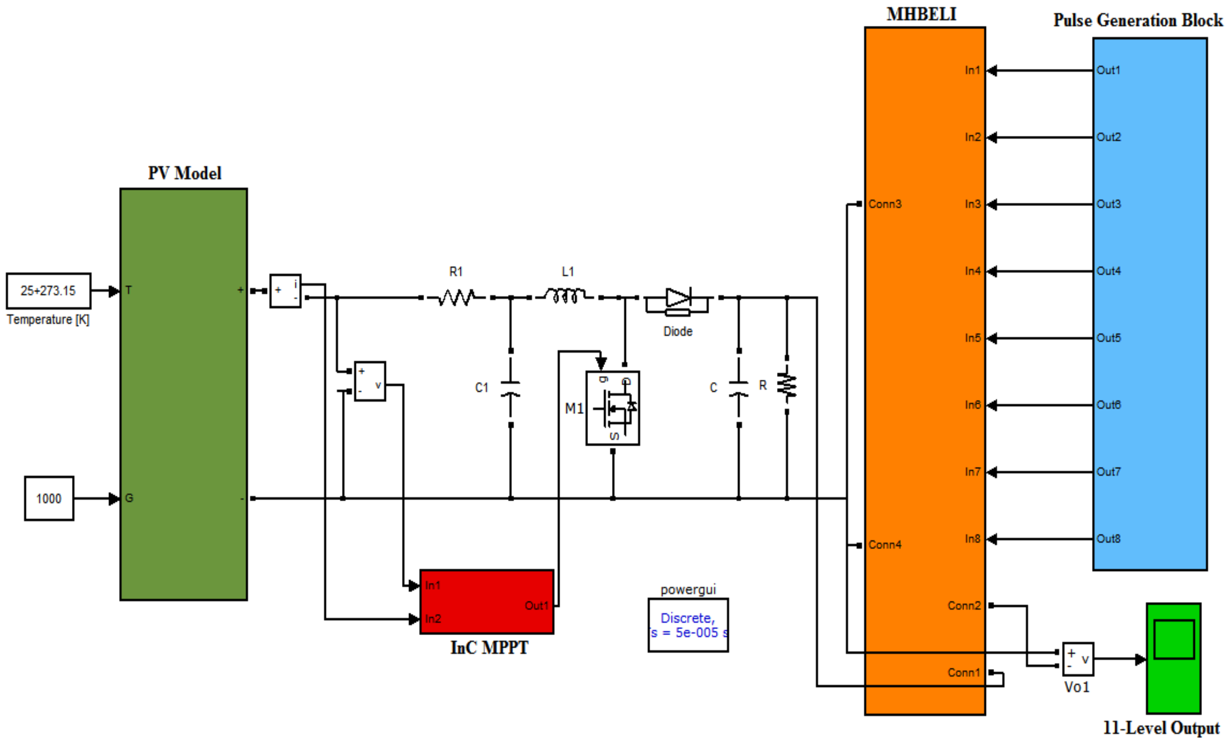

Fig. 6: Simulation of PV based single-phase MHBELI

Table 2: PV module specifications

Parameters	Ratings
Maximum power	250W
Short circuit current, I_{sc}	8.76A
MPPT current, I_{MPPT}	8.24A
Open circuit voltage, V_{oc}	37.47V
MPPT voltage, V_{MPPT}	30.34V
No. of cells	60 cells

Model: ET-P660250WB, polycrystalline

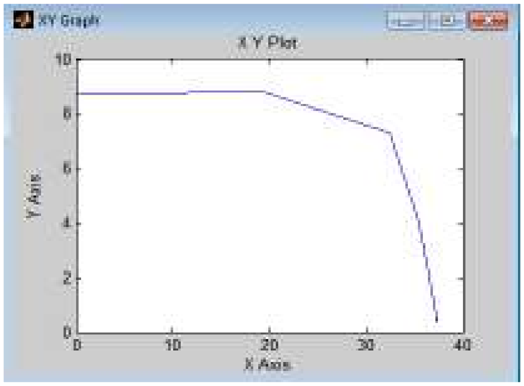

Fig. 7: Simulated I-V characteristic

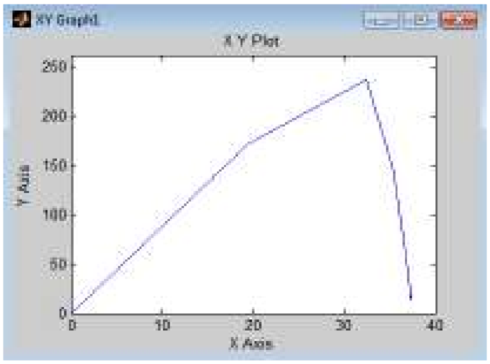

Fig. 8: Simulated P-V characteristic

The above equations can be rewritten as:

$$\frac{\Delta I}{\Delta v} = -\frac{I}{v}, \text{ at MPP} \tag{7}$$

$$\frac{\Delta I}{\Delta v} > -\frac{I}{v}, \text{ left of MPP} \tag{8}$$

$$\frac{\Delta I}{\Delta v} < -\frac{I}{v}, \text{ right of MPP} \tag{9}$$

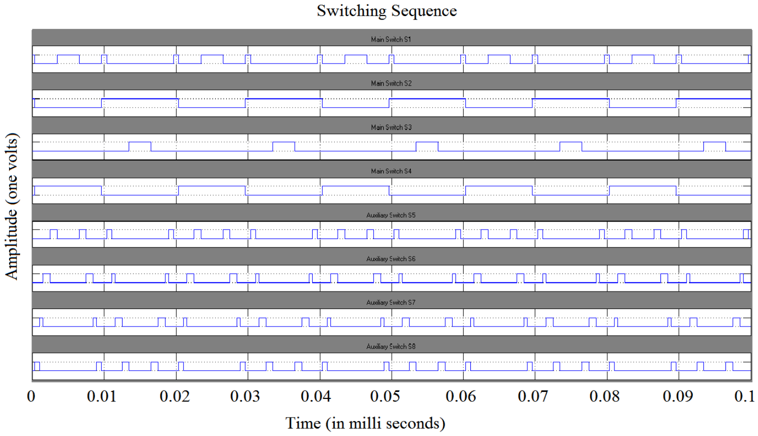

Fig. 9: Switching sequence for MHBELI circuit

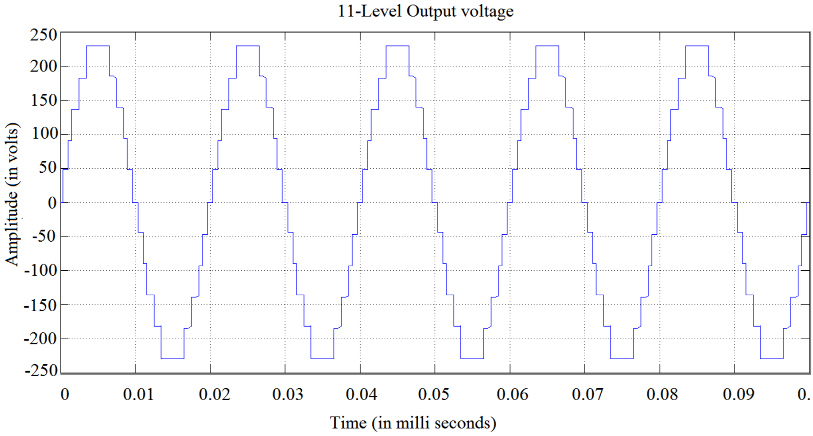

Fig. 10: Eleven-level output voltage

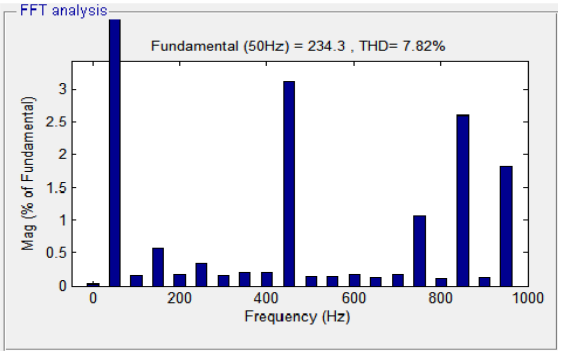

Fig. 11: FFT response of single-phase MHBELI

The MPP can thus be tracked by comparing the instantaneous conductance (*I*/*V*) to the incremental conductance ($\Delta I/\Delta V$). *Vref* is the reference voltage at which the PV array is forced to operate. At the MPP, *Vref* is equal to *VMPP*. Once the MPP is reached, the operation of the PV array is maintained at this point unless a change in ΔI is noted, indicating a change in atmospheric conditions and the MPP.

Single-phase MHBELI: The switching sequence required for the single-phase MHBELI circuit is shown in Fig. 9.

Figure 10 show the simulated output voltage waveform taken from the load terminals. It is clearly visible that the simulated output is very close to the ideal output defined for a eleven-level inverter circuit.

The eleven-levels of voltages are $+V_{dc}/5 = 46V$, $+2V_{dc}/5 = 92V$, $+3V_{dc}/5 = 138V$, $+4V_{dc}/5 = 184V$, $+V_{dc} = +230V$, 0V, $-V_{dc}/5 = -46V$, $-2V_{dc}/5 = -92V$, $-3V_{dc}/5 = -138V$, $-4V_{dc}/5 = -184V$, $-V_{dc} = -230V$ for the scale Horizontal: 10 ms/division and Vertical: 50V/division.

The Total Harmonic Distortion (THD) of the single-phase MHBELI is observed that 7.82% without filter circuit and the fundamental voltage is observed that 234.3V (50 Hz) that has been illustrated in Fig. 11.

CONCLUSION

The modeling of PV based single-phase MHBELI was done and simulated using MATLAB SIMULINK. The development of simulation model has been successfully simulated and the results of PV characteristics, Incremental conductance MPPT, switching sequence for single-phase MHBELI and output voltage waveform were obtained. The concurrence between the theoretical forecasts and simulated results show clearly that the developed simulation model works as expected PV based single-phase MHBELI and provides a broad approach on solar energy based multilevel inverters. The proposed model has obvious advantage of using single phase supply and it can be implemented using an embedded system. This approach can be used for grid connected photovoltaic energy applications.

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