Design a Switched DC Sources based Multilevel Inverter for PV System

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ABSTRACT

Integration of the renewable energy sources into the ac power grid is the most challenging task for the researchers and because of the limited resources of fossil fuels, it is the necessity of the modern time period to integrate the non-conventional sources into the ac power grid for the reliable future of the power system. The usage of photovoltaic (PV) cells is dramatically increasing very rapidly in each department of life because of their small environmental impacts, pollution-free benefits, require little maintenance, and zero noise capacity. The research work focuses on the integration of the PV system with the newly proposed topology called the switched dc sources based multilevel inverter for low, medium, and high power applications. The output of both PV panels is used as input dc voltage sources to the proposed inverter. The Phase Opposition Disposition (POD) switching technique of Pulse Width Modulation (PWM) is employed for the switching of the power switches of the new topology inverter. The Perturb and Observe (P&O) algorithm of Maximum Power Point Tracking (MPPT) controls each array in the PV system. To obtain the constant output voltage from the PV system, the P&O algorithm is used to control the duty cycle of the DC-DC boost converter. The single-phase five-level inverter is utilized for the conversion of the dc power obtained from the PV array into the ac power. The waveform of the output voltage and current are obtained and its THDs is analyzed. The overall device count is reduced and the better output quality of the waveform is obtained with the usage of a fewer number of power switches than conventional topologies. The performance of the single-phase five-level switched dc sources based multilevel inverter for PV system, is evaluated in the MATLAB/Simulink software.

General Terms

Maximum Power Point Tracking, Multilevel Inerter, Perturb and Observe Algorithm, Phase Opposition Disposition, Pulse Width Modulation, Photovoltaic.

Keywords

MPPT, MLI, P&O, POD, PWM, PV, Switched DC Sources Based Multilevel Inverter, THD.

1. INTRODUCTION

The recent developments in power electronics have captured the focus of the world to generate more amount of electrical energy from non-conventional energy sources. The main renewable energy sources that come into the consideration of the researchers and scientists are solar and wind energy [1]. The Photovoltaic (PV) system is a combination of components that enables us to harness the power of the sun in our own houses, businesses, or to a large level. It converts the solar radiations directly into electrical energy with a simple electrical structure and without the usage of any moveable device. Due to this feature, its usage is increasing very fast at the places where the main national grids unable to supply electrical energy because of any reason or where the reduction in noise level is required [2]. The PV modules are made from a collection of solar cells, typically PV modules are made from a number of crystalline silicon solar cells. These solar cells will be mounted on a structure and will be interconnected to form a module. Two or more solar panels will be wired and interconnected either in series or in parallel to form a solar panel. Two or more solar arrays will be wired and interconnected together either in series or in parallel to form a solar array. [3]. There are various ways of organizing the cells in a module that affects the characteristics of a module [4]. In series connection of solar cells, the open-circuit voltage of each module will be added and the current remains constant [5]. On the other hand, in parallel connection of solar cells, the current of each cell will be in addition and voltage remain constant [6, 7].The PV system includes all the components required to convert the energy from the sun and be able to use it with regular appliances. Usually, this consists of two main components, a PV module, or several, and an inverter [8]. Depending on the topology of the system there might also require a battery. Among all of the components, the inverter is the most expensive part and should be selected very carefully. Its cost depends upon two elements; the quantity of the input dc voltage sources and the quantity of power switches [9].

The multilevel voltage-source inverters have made it possible to integrate renewable energy sources into the grid. The benefits of multilevel (MLIs) are that it reduces the stress on the load [10]. It has three types; 1) cascaded H-bridge (CHB) 2) neutral point clamped (NPC), 3) flying capacitors (FC). Among them all, the cascaded H-bridge (CHB) finds it most suitable due to its modest structure and its output can be governed with multiple methods. It can be classified into two categories based on input dc voltage sources; 1) Symmetrical sources 2) Asymmetrical sources. In symmetrical sources, the amount of voltage supplied to the input will be the same and the output would be the sum of all the input sources. This is not a good method if the number of levels required is high. On the other hand, asymmetrical sources required different amounts of supplied voltages and it is widely implemented when the greater voltage output level is required. Multilevel inverters are used for converting the power from ac-to-dc in medium and high power applications but researchers are now introducing new ways to use it in low power applications as

well [10, 11]. The quality of the sinusoidal waveform can be enhanced by increasing the number of levels of the multilevel inverter. However, by increasing the number of levels the overall size, cost, and gate drive circuits will also increase. This makes the overall circuit most complex, costly, and bulky. Therefore it is required to propose such topology in which the number of levels can be increased with fewer components. Researchers are working very hard to introduce new topologies that can be helpful in reducing these problems [12]. The paper presents a new topology wherein the two reverse isolated dc sources are connected across power switches. This topology best-fitted in the integration of the PV arrays into the ac-power grid while maintaining the stability and synchronism of the power system [13].

In twenty-four hours of a day, the solar radiations and its temperature vary, and as a result of that the generation of the power from PV is not the same and there is a dire need for such an algorithm which can operate the PV arrays on maximum power. The researchers have used many maximum power point tracking (MPPT) algorithms but the most suitable algorithms are two i.e. Perturb and Observe (P&O) and Incremental Conductance (IC). For to obtain the maximum power from the PV arrays, the P&O algorithm of MPPT is employed [14].

Herein, a single-phase five-level inverter is used for the conversion of power from ac-to-dc obtained from a PV system. Two solar panels each rated as 50 W having a symmetric output of 24 V approximately works as an input dc voltage sources for the proposed topology. The P&O algorithm of MPPT is employed to obtain the maximum power from the sets of 50 W solar panels as possible [15]. The Phase Opposition Disposition (POD) switching technique of multicarrier pulse-width modulation (PWM) is used for the switching of the proposed topology [16]. The Total Harmonic Distortion (THD) of output voltage and the output current is reduced to a much greater extent in order to meet the international scientific standards. To simulate this research work, the platform of MATLAB/SIMULINK is used and the simulation results are presented and discussed.

1.1 Types of Photovoltaic (PV) System

There are three types of photovoltaic (PV) system depending on the type of applications one would choose which system one need to install. There are three types of the PV systems [10, 11]:

a) OFF-Grid PV System
b) ON-Grid PV System
c) Hybrid PV System

a) OFF-Grid PV System

It is used on a small scale especially in rural areas where the shortage of power is the main problem. In this system a battery backup system is necessary which charges with the help of PV panels during day time and consumes that energy in night [12]. It is economical system. The block diagram of the system is shown in Fig. 1.
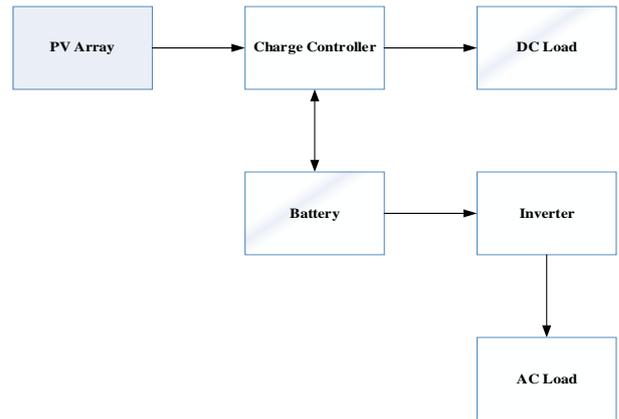
Figure 1 OFF-Grid PV System

b) ON-Grid PV System

ON-grid or grid-connected PV system works in synchronization with the grid or utility supply. It is the basic requirement whenever the on-grid solar system is installed a grid connection must be available for the facility [13]. The block diagram of the system is shown in Fig. 2.
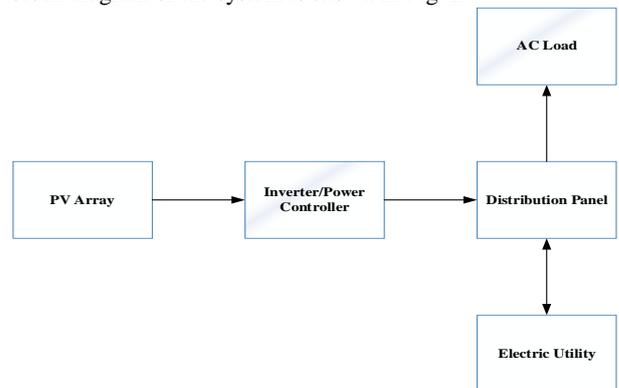
Figure 2 ON-Grid PV System

c) Hybrid PV System

In this system the combination of both methods (i.e. OFF-grid and ON-grid PV system) is utilized. The consumer consumes the energy and the extra energy will be sent to the grid and the total bill will be the subtraction of both the consumed and produced energy. This process is called net-metering. The block diagram of the system is shown in Fig. 3.
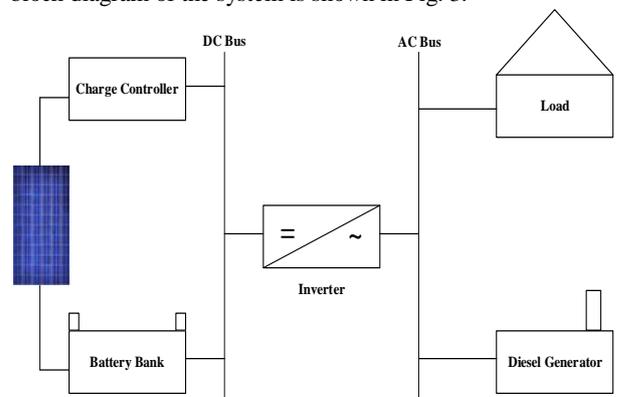
Figure 3 Hybrid PV System

2. BOOST CONVERTER

The boost converter allows the step-up of a lower input voltage into a higher output voltage with to a certain extent of a simple electric circuit. It can raise the voltage of DC sources such as batteries or solar cells. By suitable selection of duty ratio cycle "d", maximum power can be achieved from any of the PV system [16]. Fig. 4 shows the arrangement of the system in which the continuous sensing of voltage and current of PV system is carried out.
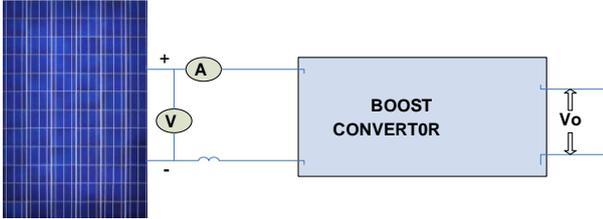
Figure 4 PV and Boost Converter

$$Vout = (\frac{1}{1-D}) \qquad (1)$$

$$Iout = (1-D)Ipv \qquad (2)$$

To tune the duty cycle "d", the continuous sensing of voltage and current of a PV array is required. The output of both parameters (i.e. current and voltage) will be given to MPPT [17]. Within the MPPT, the P&O algorithm is utilized which calculate the appropriate value of duty ratio cycle"d", and then it gives the output to the gate driver which finally gives the firing pulses to the power switch in the boost converter. The output of boost converter is connected with proposed inverter as input dc voltage sources [18]. The complete prototype is shown in Fig. 5.
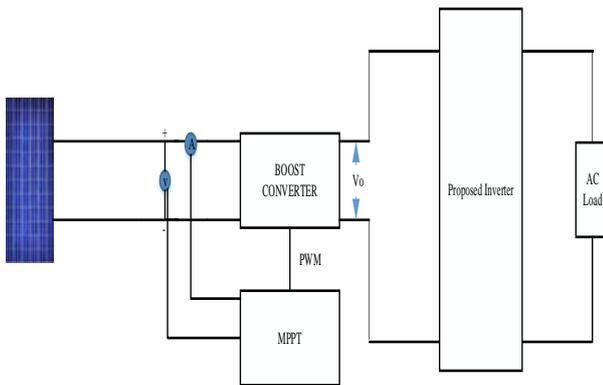
Figure 5 Boost converter with PV panel and the proposed inverter

2.1 Perturb & Observe algorithm of Maximum Power Point Tracking

During the day sun changes its radiation as well as temperature. Accordingly, the irradiation and temperature on the photovoltaic (PV) panel continuously changes which negatively affects the performance of PV module [19]. It effects the efficiency of the PV panel and it cannot operate on maximum power. Therefore, the need of such an algorithm emerges that nullify these problems. [20]. The goal is to find the voltage at which the solar panel outputs the most power, V_{mpp}. Once V_{mpp} found, with the usage of some power

electronics to make sure that this voltage is applied to the solar panel [21]. The MPPT continuously makes incremental changes to the voltage and monitor changes in power. If the change in voltage increases the power output of the solar panel, the next perturbation will be in the same direction. Unlike if change in voltage decreases power output of solar panel, then the next perturbation will be in the opposite direction [22]. Table 1 shows all the possibilities.

Table 1 decision of the perturbation

Prior Perturbation	Change in power	Next Perturbation
+	+	+
+	-	-
-	+	-
-	-	+

3. SINGLE-PHASE SWITCHED DC SOURCES BASED MULTILEVEL INVERTER

The new configuration inverter in combination with PV system is presented in Fig. 6 while a generalized model of single-phase switched DC sources based multilevel inverter is explained here.
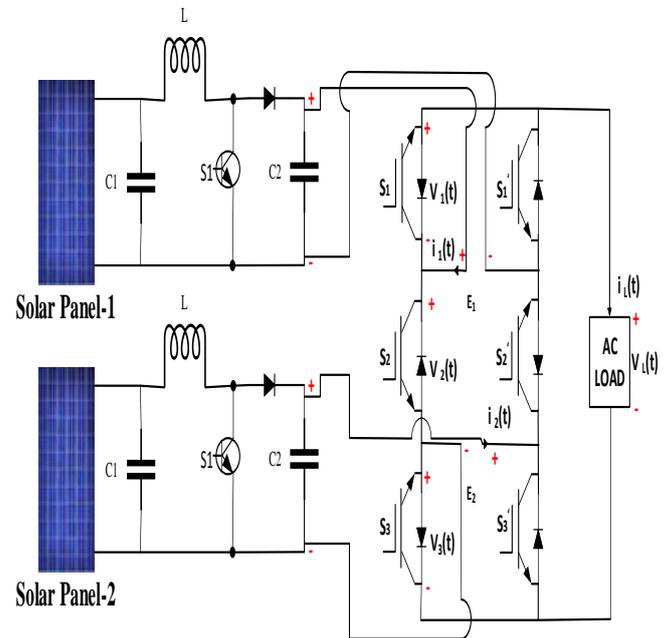
Figure 6 Proposed Inverter Topology for PV

To find the mode of the operation, the output voltage level is seen. Hence there is six modes of operations as displayed in Fig. 7 and are briefed in Table 2 with the help of nodal voltages as well as source currents. Here six power switches are used (S_1, S_2, S_3, S_1', S_2', and S_3').

With the help of mode of operation, there will be five-levels, i.e. $\pm V_{dc}$, $\pm 2V_{dc}$ and zero. The source will be symmetric like

$PV_1 = PV_2 = V_{dc}$. Modes 2 and 3 will be responsible for $+V_{dc}$, on the other hand, modes 4 and 5 will be responsible for $-V_{dc}$. The very important point to consider here is that, in modes 1, 2, and 3, for positive voltage levels and one zero level, the power switch S_2' will always conduct. On the other hand the modes 4, 5, and 6, for all the negative levels, the power switch S_2.

Table 2 Modes of operation

Mode	Switch Condition (1 for ON and 0 for OFF)			Output Voltage $v_L(t)$
	S_1	S_2	S_3	
1	0	0	0	0
2	1	0	0	$+V_{dc}$
3	1	0	1	$+2V_{dc}$
4	0	1	1	$-V_{dc}$
5	0	1	0	$-2V_{dc}$
6	1	1	1	0
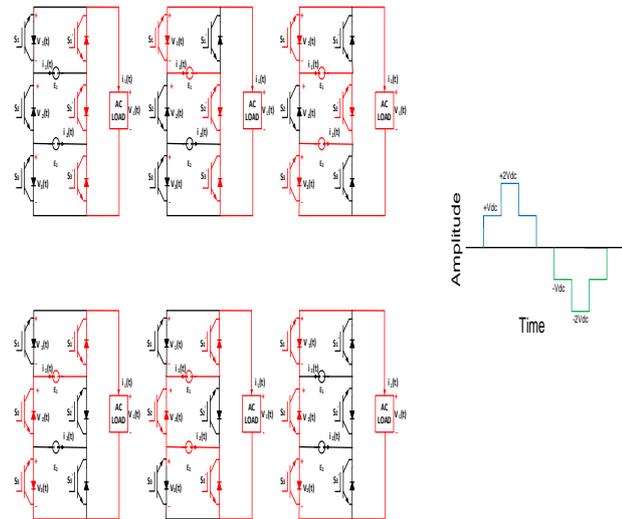
Figure 7 Circuit diagram of modes of operation

3.1 Modulation Technique

The switched dc sources based multilevel inverter can be modulated with any of the modulation techniques. In this research work, the multicarrier PWM switching technique is utilized where one reference and four carrier signals are compared with each other and the pulses obtained from this comparison are used for the switching of the power switches. Hence by using six modes (i.e. 1, 2, 3, 5, 6, and 8), the power switches S_2 and S_2' will must operate and bear the voltages stress of $2V_{dc}$. On the other hand, the leftover switches will bear the voltage stress of V_{dc}. The proper utilization of all the modes is necessary in order to obtain five-level output. It must be noted here that this control technique can be used for higher-level inverters as well [1].

The four triangular waveforms of each 1-kHz are compared with a single sinusoidal wave of 50-Hz. The carrier signals above the zero reference is classified as positive and below the zero reference is classified as negative. It is also worth mentioning that only S_2 and S_2' will work at the fundamental frequency (i.e. 50-Hz), whereas all the remaining power switches i.e. S_1, S_1', S_3 and S_3' will operate at 1-kHz. The two input dc sources will be used as $E_1 = E_2 = V_{dc} = 24$ V, hence the proposed topology will use symmetric dc sources.

4. RESULTS AND DISCUSSIONS

The simulated model of the switched dc sources based MLI for PV system is displayed in Fig. 8. Herein, two PV solar modules each having power of 50W are connected as the input source of the switched dc sources based MLI. The inverter is simulated with the symmetric input dc voltage sources. Therefore, the output of both PV solar modules are approximately of 24V. The simulated inverter converts the dc power into an ac power. P&O algorithm of MPPT is employed for the controlling of the power switch of the boost converter to obtain the required duty cycle which is best for the improvement and performance of PV solar modules. By increasing or decreasing the value of duty cycle with the help of P&O of MPPT, the performance of a PV solar module is checked.
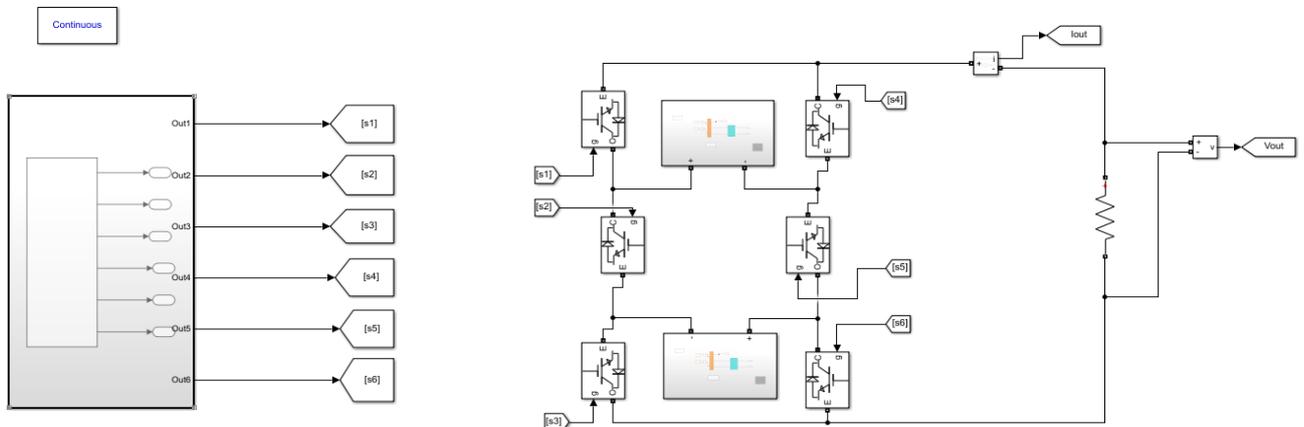
Figure 8 simulation model of switched dc sources based multilevel inverter for PV system

4.1 Photovoltaic (PV) panels and boost converter specification

The parameters of the PV solar Modules connected to the switched dc sources based MLI are shown in Table 3.

Table 3 PV Solar Module-1 and PV Solar Module-2 Specifications

Parameters	Value
Module	User-defined
Maximum Power (W)	50 W
Open-circuit voltage, V_{oc}	21.6 V
Short-circuit current, I_{sc}	3.13 A
Voltage at maximum power, V_{mp}	17.5 V
Current at maximum power, I_{mp}	2.87 A
Temperature coefficient of Voc (%/deg.C)	-0.37(%/deg.C)
Temperature coefficient of Isc (%/deg.C)	0.06 (%/deg.C)
Parallel strings	1
Series-connected modules per string	1

The specifications of boost converter of PV Solar Module-1 and PV Solar Module-2 are listed on Table 4.

Table 4 Boost converter specifications for PV Solar Module-1 and PV Solar Module-2

Electrical Components	Ratings
Input Capacitor, C_{in}	1 µf
Inductor, L	177 µH
Resistor, R	0.005 Ω
Input Capacitor, C_{out}	158 µf

The overall research work specifications of the research work is shown in Table 5.

Table 5 Overall research work specifications

Parameters	Details
Total Photovoltaic (PV) sources as input dc voltage	2-symmetric input dc voltage of each 24 V (Approx.)
Total number of power electronic switches	6 power electronic switches

Output voltage levels	5 levels
Resistor value	2 Ω
Inductor value	2 mH

The output waveforms of the voltage and current of PV Solar Module-1 and PV Solar Module-2 are shown in Fig. 9 and Fig. 10.
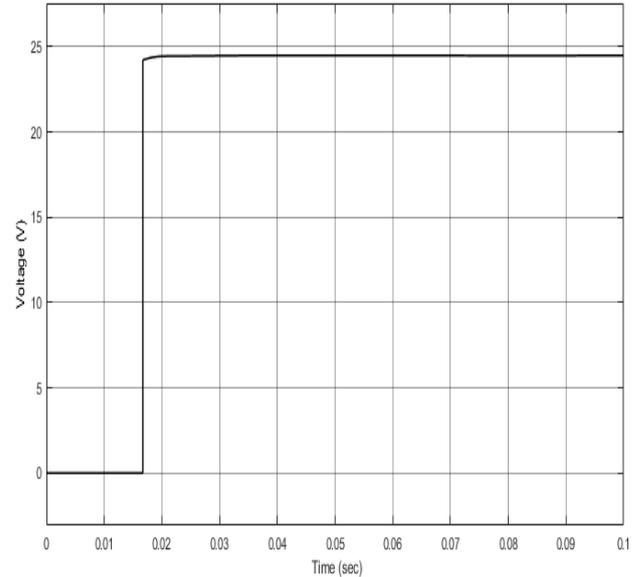
Figure 9 PV Solar Module-1 and PV Solar Module-2 output voltage waveform
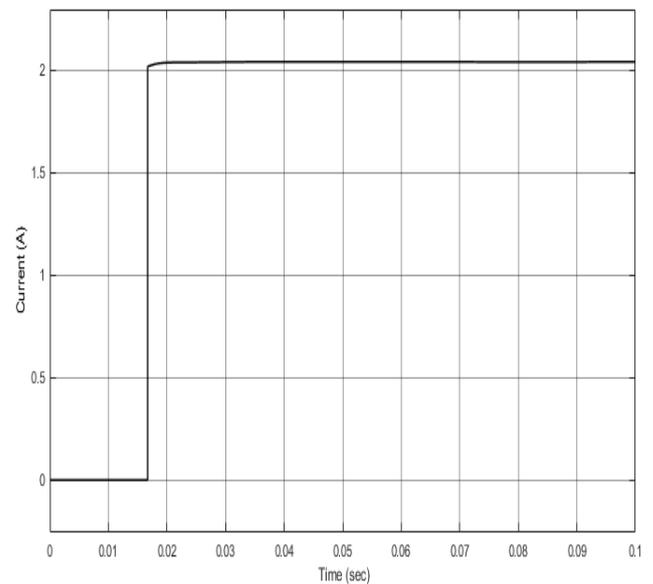
Figure 10 PV Solar Module-1 and PV Solar Module-2 output current waveform

The output waveform of the power of PV Solar Module-1 and PV Solar Module-2 are shown in Fig. 11.
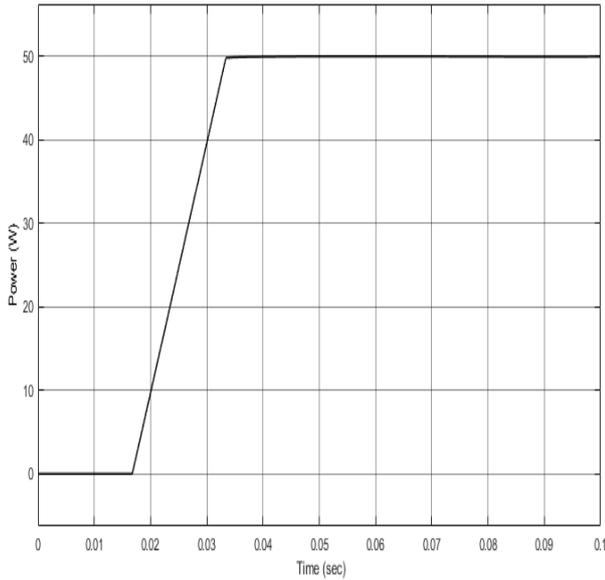
Figure 11 PV Solar Module-1 and PV Solar Module-2 power output waveform

4.2 POD Multicarrier PWM

The Phase Opposition Disposition (POD) of the carrier PWM modulation technique is used here in which the sine wave signal is being compared with the four triangular wave signals in order to achieve five level output. The carrier signal above the zero reference is called positive carrier signals and the carrier signals below the reference is called the negative reference signals.
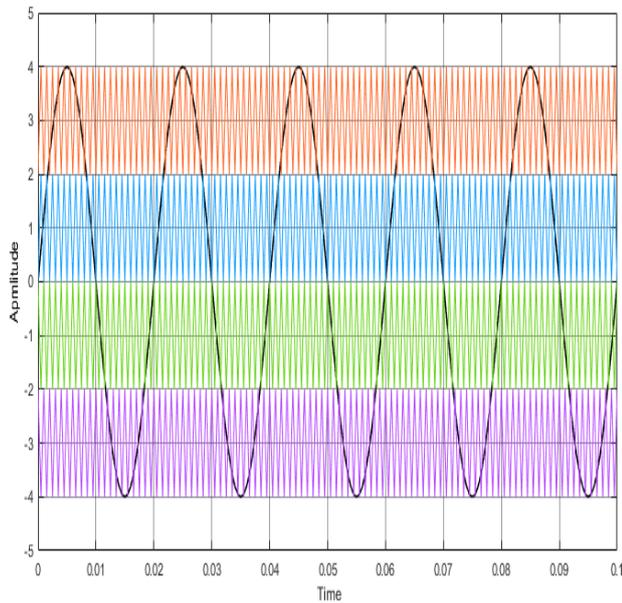
Figure 12 Phase Opposition Disposition Carrier PWM

The control signal of the six power electronic switches are shown in Fig. 13 in which the switch S_1 and S_3 will work on the fundamental frequency i.e. 50-Hz, while all other remaining switches will operate on the specified frequency i.e. 1-kHz.
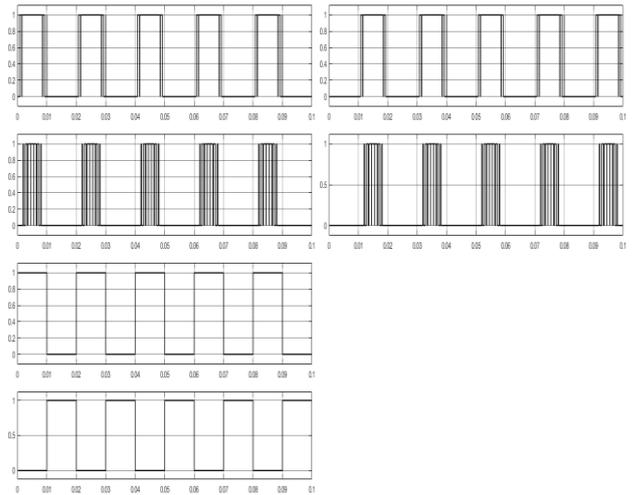
Figure 13 Control signals of power switches
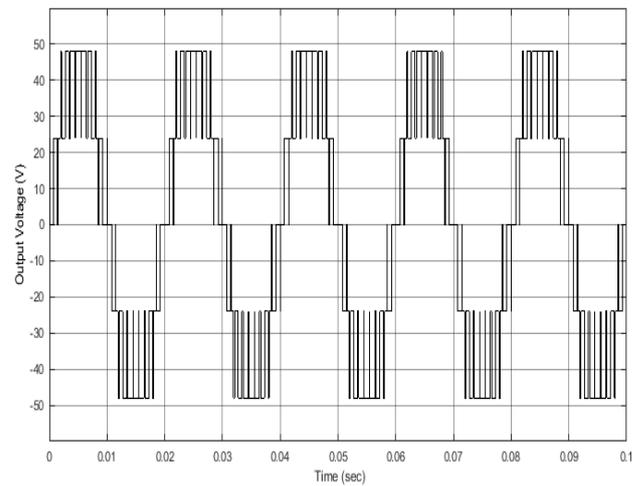
Figure 14 Output voltage waveform
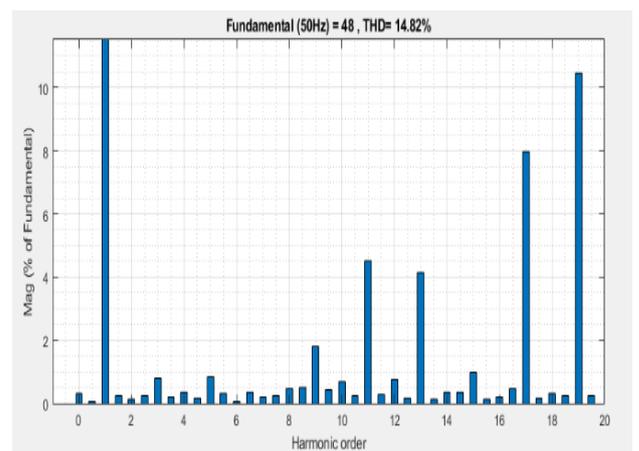
Figure 15 Output voltage THD

While integrating the PV-1 as input dc voltage source as V_1 and the PV-2 as input dc voltage source as V_2 with the proposed inverter, obtained output voltage has five-levels and its THD are about to 14.82% (displayed in Fig. 14 and Fig. 15).The obtained output current waveform and its THD are presented in Fig. 16 and Fig. 17. The output current waveform

has a THD of 5.72%. The proposed inverter has proven its capacity to give five-level output with P&O MPPT algorithm with symmetric input dc sources i.e. PV-1=V_1 and PV-2=V_2. The five-level output voltage contain 0, V_{dc}, $2V_{dc}$, -V_{dc}, and -$2V_{dc}$ that contain output voltage as 0, 24 V, 48V, -24 V, -48V.
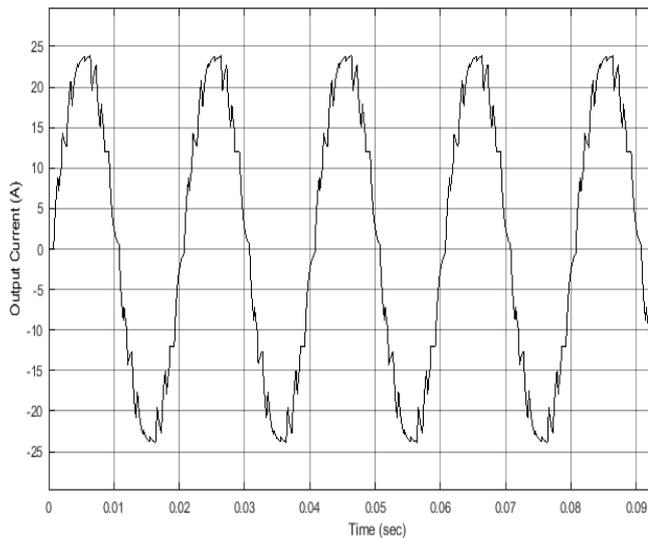
Figure 16 Output current waveform
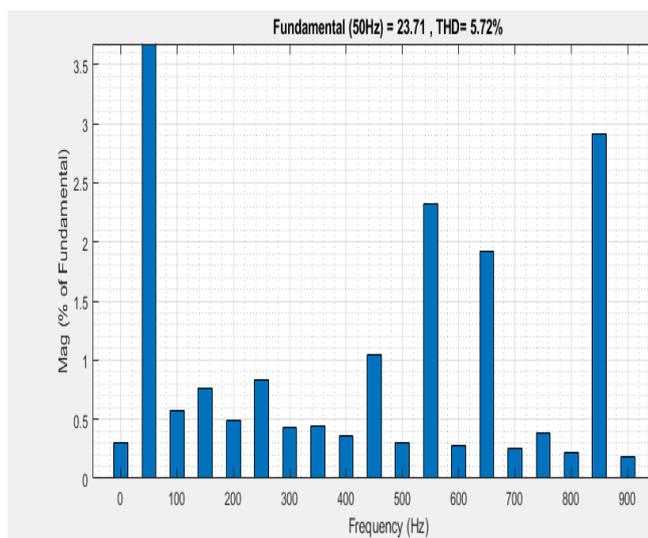
Figure 17 Output current waveform THD

5. CONCLUSION

The paper present the single-phase five-level switched dc sources based MLI used for the conversion of the dc power achieved from a PV module to an ac power. The two PV systems, PV-1 and PV-2 of equal amplitude works as a symmetric input dc sources for the proposed inverter. The component count (input dc sources and power switches) is reduced and for the proper switching of power switches, the Phase Opposition Disposition (POD) technique of Pulse Width Modulation (PWM) is employed. To obtain the constant output voltage from the PV system, the P&O algorithm is used to control the duty cycle of the DC-DC boost converter. The total number of power electronic switches are decreased and decent clear quality of wave is obtained. The overall model construction is simple and has

improved THDs in voltage and current while integrating with the photovoltaic (PV) system. The research work is simulated via MATLAB/Simulink computer software platform and have examined its different parameters and thus reduced the total THDs in the voltage and current.

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