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Modeling and analysis of a quasi-linear multilevel inverter for photovoltaic application

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Abstract

A quasi-linear Cascaded H-Bridge multilevel inverter is introduced for solar application. In this paper, a separate solar panel with boost converter is placed instead of DC sources in the proposed configuration. The Incremental and Conductance maximum power point algorithm method is implemented for tracking maximum power with a fast response. Sinusoidal reference with triangular carriers is utilized in pulse width modulation for generating the switching pulses for proposed inverter. The proposed inverter can generate a 19-level output voltage with total harmonic distortion of 6.10% which is simulated using MATLAB/Simulink. Cost analysis of power switches is discussed.

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Keywords: Grid connected MLI; boost converter; hybrid multilevel iinverter; pulse width modulation;single phase grid.

1. Introduction

Renewable Energy Sources (RES) such as the wind, solar, biomass are employed to avoid the ecological problems such as global warming and air pollution caused by fossil fuels [1]. The cost of photovoltaic modules has reduced over the last decades. So, Solar energy is the cheapest energy source when compared to other RES also nowadays solar plant with Megawatt range are becoming a standard in many countries [1,2]. Multilevel inverter (MLI) proved as substantial global attention by the researchers and industries in the applications of renewable energy system integration, AC motor drives and grid power quality [2]. The features of MLI are developed to other applications such as electric ship propulsion, aircraft, hybrid electric vehicle, multiphase drives and traction systems.

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Single phase MLIs are becoming more popular in medium power microgrid applications because it can able directly connected to the grid without any transformers [3]. Different types of PV based grid connected inverters are the central inverter, string inverter, multi-string inverter, AC module inverter, and cascaded H-Bridge (CHB) inverters [4]. CHBMLI is being investigated as an interesting topology in grid connected solar application. Different types of reduced switch topologies for grid connected solar application are developed and presented in [5]. The main disadvantage of these reduced switch inverter topologies is not possible to generate all additive and subtractive combinations of the input DC sources. In CHBMLI is the appropriate choice for generating output voltage levels in all the combination and also utilized for high voltage applications. Asymmetric MLI provides getter better output voltage level when compared to symmetric MLI [5].

In this paper, PV based grid connected CHBMLI is developed and it is operated at quasi-linear ratio (asymmetric). Incremental and Conductance method is used for tracking the maximum power. Sinusoidal reference with triangular carriers is used for generating the switching pulses. Three boost converters are designed based on the quasi-linear ratio and PV panel input voltage. Simulation results are shown to prove the effectiveness of grid connected quasi-linear multilevel inverter.

2. Modeling of PV System

A mathematical model for PV cell with the single diode and two resistors (series & parallel) combination is discussed in this section. The equivalent circuit of PV cell is shown in Fig. 1. Table 1 shows the 80 W PV panel rating. The mathematical formula for PV cell using the below formula [6]

$$I = I_{PV,cell} - I_{o,cell}\left[exp\left(\frac{qv}{akT}\right) - 1\right] \tag{1}$$

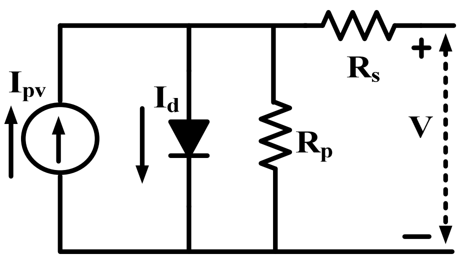

Fig. 1. Equivalent circuit diagram of PV cell

Table 1. Rating of 80 W PV Panel

Parameter	Values
Short circuit current	4.71 A
Open circuit voltage	22.24 V
Maximum power point voltage	18.33 V
Maximum power point current	4.37 A

A PV module is formed by connecting several PV cells are connected in series and parallel. Fig. 2 shows the I-V curve and P-V curve. The mathematical formula for PV arrays using the below formulas

$$I = I_{PV} - I_o\left[exp\left(\frac{V + R_s I}{V_t a}\right) - 1\right] - \frac{v + R_s I}{R_p} \tag{2}$$

$$I_{PV} = \left[I_{PV,n} + K_I \Delta_T\right]\frac{G}{G_n} \tag{3}$$

$$I_o = \frac{I_{SC,n} K_I \Delta_T}{\exp\left[\left(V_{oc,n} + K_I \Delta_T\right)/a v_t\right] - 1} \tag{4}$$

The PV panel is designed and tested at Standard Test Condition (STC). The detailed explanation of modeling the solar panel is discussed in [6]. To track the maximum point of voltage and current in IV-curve and PV-curve, Incremental and Conductance MPPT is used. This MPPT technique provides a fast response when compared to the P&O technique. The design of MPPT technique is explained in [6].

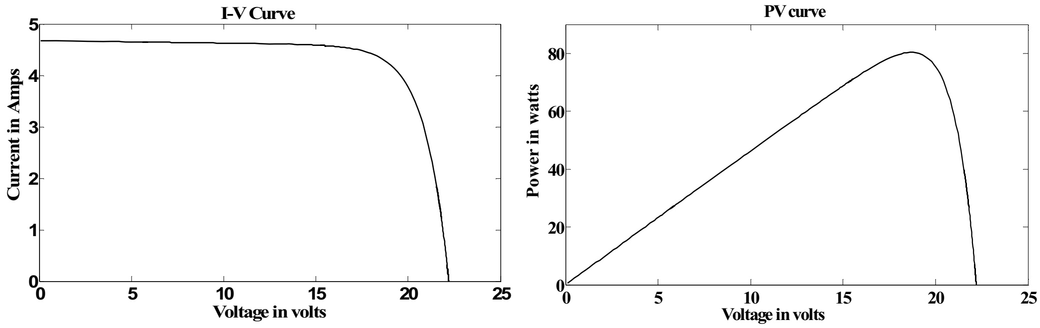

Fig. 2. (a) I-V curve (b) P-V curve

3. Modeling of Boost Converter

A DC-DC Boost Converter is used in the proposed grid connected MLI system. According to the proposed topology, three separate DC-DC boost converters are needed with different ratings. The output of each solar panel is connected to the separate boost converter. Each boost converter output voltage is directly connected to the proposed MLI. The boost converters are designed and operated in the continuous conduction mode. The design of inductor and capacitor is based on the converter switch open and close time periods. The notation 'D' represents duty ratio, if 'D' increases, the boost output voltage will increase. But the duty ratio closely approach to the value of 1 then the output voltage goes to infinity. The output voltage of each boost converter is connected to the quasi-linear CHBMLI. The Duty ratio (D), inductor (L) and capacitor (C) are calculated using the below formula

$$D = 1 - (V_{in}/V_{out}) \quad (5)$$

$$L = \frac{V_{in}DT}{\Delta_{iL}} \quad where\ \Delta_{iL} = (3\% \times I_{out}) \quad (6)$$

$$C = \frac{I_{out}DT}{\Delta_{vo}} \quad where\ \Delta_{vo} = (3\% \times V_{out}) \quad (7)$$

4. Modeling quasi-linear multilevel inverter

Cascaded H-Bridge MLI consists of several H-Bridge are connected in series. The combination of CHB in series connection utilized for large and medium power applications. The main aim of selecting MLI in grid connection application is high power injection to the grid without use of transformer. In [8], each PV panel has same rating and generates the same voltage which is connected to CHBMLI. So, it will acts as symmetric MLI but in this paper, CHBMLI act as an asymmetric condition so each PV panel output is connected to the CHBMLI through boost converter. The boost converter is used to boosting the output voltage from PV panel based on the quasi-linear condition. Fig.3. shows the circuit diagram of PV based grid application quasi-linear CHBMLI.

The value of input DC source as follow the below equation

$$V_{dc,n} = \begin{cases} V_{dc} & n = 1 \\ 2 \times 3^{n-2} V_{dc} & n \geq 2 \end{cases} \quad (8)$$

The output voltage level for quasi-linear CHBMLI as follows the below equation

Output voltage level = $1 + \sum_{n=2}^{\infty} 2 \times 3^{n-1}$ (9)

Based on the equation (8) and (9), the 19-level output voltage can generate using three DC sources and 12 switches whereas eight DC sources and 32 switches utilized for generating the same output voltage level in [4,7].

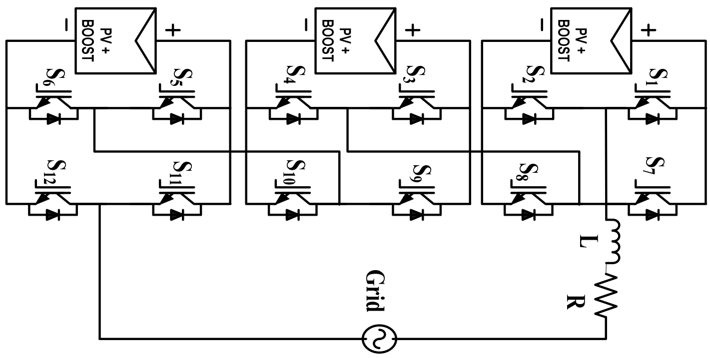

Fig. 3. Grid connected quasi-linear MLI

5. Cost analysis of power electronic switch

The cost of power switches is depending on the factor of α . The factor of α is defined as the ratio of cost of power switches rated at double output voltage to the cost of power switches at output voltage with the same current rating. Table 2 shows the cost analysis and power ratings of three different IGBT switches. The factor value may be varying depends on power ratings of switches. Per unit cost of power switch for CHB and other developed topologies could be compared with this factor value. The cost value can be directly depend on number of switches utilized and indirectly depend on number of levels.

6. Simulation Results

The proposed PV based quasi-linear CHBMLI for grid application is simulated using MATLAB/Simulink. The ratio of three DC sources is 1:2:6. In this paper, instead of DC sources separate PV panels with boost converter is utilized. The first and second DC sources are replaced by separate 80 W panels with Incremental and Conductance MPPT through boost converter. The third DC sources are replaced by three 80 W panels are connected in series and passes through boost converter. So, the overall quasi-linear MLI is operated at 400 W. The gating pulses are generated by using sinusoidal pulse width modulation (SPWM). The 19-level output voltage is generated by utilization of 18 carriers. The carriers are each in phase with the same amplitude and same frequency that is called Phase Disposition (PD) [9] as shown in Fig.4.a. The boost converter switching frequency is 24000 Hz. The inverter switching frequency is 3000 Hz. The output voltage waveform and harmonic spectrum plot for quasi-linear MLI as shown in Fig.5.a and Fig.5.b.

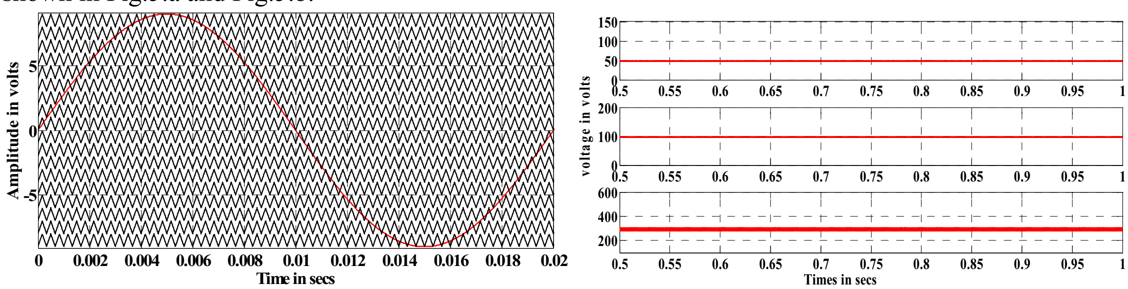

Fig. 4. (a) Carrier arrangement for PD strategy (b) Three different boost converter output voltages

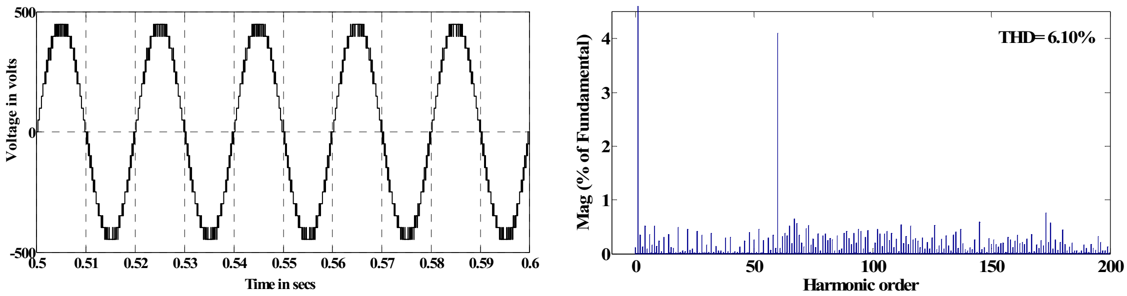

Fig. 5. (a) 19-level output voltage; (b) Harmonic spectrum plot (without filter inductance)

Table 2. Cost Analysis of power switch (IGBT) as on 16.03.2015

S.No.	Switch name	Voltage	Current	Cost(USD)	Factor Value(α)
1	FS15R06XL4	600	15	23.08	0.5321
	FS15R12VT3	1200	15	12.28	
2	F4-100R06KL4	600	100	87.22	1.5496
	F4-100R12KS4	1200	100	135.16	
3	FF450R06ME3	600	450	104.22	3.0312
	FF450R12IE4	1200	450	315.92	

In grid application, the MLI output needs a sinusoidal waveform, so the filter inductance is added to the load. Fig.6. shows the quasi-linear MLI output voltage and grid current for grid system. The simulation voltages are designed for greater than 1.414 times of grid voltage. The filter inductance formula is calculated using the below formula [8]

$$L_f = \frac{Vf_w}{If_{sw}}\left(\frac{1}{2\pi f_{sw}}\right) \tag{10}$$

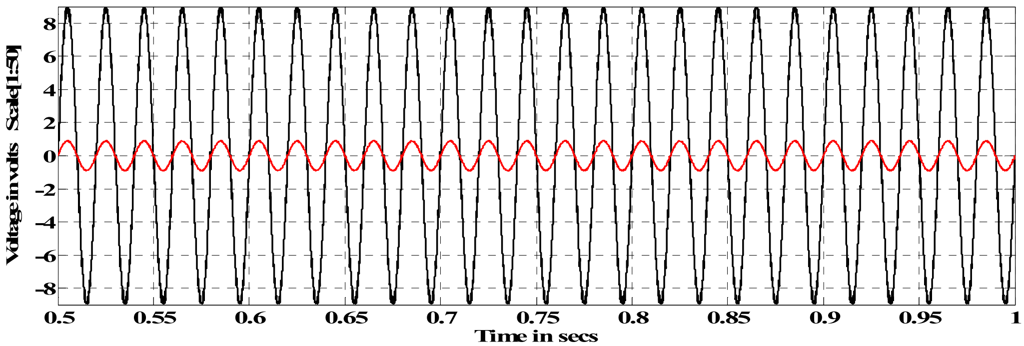

Fig. 6. Output voltage and current for grid connected quasi-linear MLI with filter inductance

7. Conclusion

A PV based grid connected quasi-linear CHBMLI has been presented for 19-level output voltage in this paper. Separate PV panels with boost converters have been utilized instead of CHBMLI DC sources. Incremental and conductance MPPT is utilized for fast response to achieve in steady state response. Sinusoidal pulse width modulation technique is used to generate the switching pulses of proposed grid connected MLI. The modeling of PV panel, boost converter and quasi-linear MLI and filter inductance is presented with the mathematical formula. The cost analysis of power electronics switch (IGBT) with different ratings has been discussed.

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