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Analysis and integration of multilevel inverter configuration with boost converters in a photovoltaic system

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ABSTRACT

This paper proposes a single phase multilevel inverter configuration that conjoins three series connected full bridge inverter and a single half bridge inverter for renewable energy application especially photo-voltaic system. This configuration of multilevel inverter reduces the value of total harmonic distortion. The half bridge inverter utilized in the proposed configuration increases the output voltage level to nearly twice the output voltage level of a conventional cascaded H-bridge multilevel inverter. This higher output voltage level is generated with lesser number of power semiconductor switches compared to conventional configuration, thus reducing the total harmonic distortion and switching losses. The effectiveness of the proposed configuration is illustrated by replacing the isolated DC sources in multilevel inverter with individual photo-voltaic panels using separate perturb and observer based maximum power point tracking and boost converters. The verification of the proposed system is demonstrated successfully using MATLAB/Simulink based simulation with different irradiation and temperature conditions. Also, the transient operation of the system is verified with results depicted using step change in standard test condition. In the proposed system, total harmonic distortion of the output voltage is 9.85% without using passive filters and 3.91% with filter inductance. Theoretical calculation of the power losses and total harmonic distortion with mathematical equations are discussed. Selective experimental results are presented to prove the effectiveness of proposed system.

1. Introduction

In recent days, to address the concern postured by conventional energy sources, for example, exhaustion of fossil powers and atmosphere changes, numerous countries are expecting to build their share of energy generation from clean energy [1]. Solar, wind, hydro and bio-fuel energies are the prime applicants of clean energy. Solar energy and wind energy have become more prominent when compared to the other renewable energy resources [2]. In India, Ministry of New and Renewable Energy (MNRE) has proposed to scale up the renewable target to about 175 GW by 2022, with over 90% of this volume accounted by solar and wind-based power. The installation of solar energy capacity has grown rapidly by 20–25% over the last few years in India because of numerous advantages offered such as reduced cost, pollution free and continuous availability in day time [1,2]. The reason for decrease in solar cost is based on factors such as increasing the efficiency of solar cells, improvement of manufacturing technology and economies of scale.

Maximum power point tracking (MPPT) plays a vital role in photovoltaic application for increasing the efficiency by tracking the maximum power from solar [3]. Irradiation and temperature are the two major factors which affect the generated voltage from PV system [4]. The usage of MPPT is to track the maximum power point during changes in the irradiation or temperature from the Standard Test Condition (STC) [3,4]. Many MPPT techniques are reported so far. A comprehensive review of MPPT for solar application is reported in [5,6]. The metaheuristic algorithms may require

Abbreviations: MLI, multilevel inverter; PV, photovoltaic; THD, total harmonic distortion; CHBMLI, cascaded H-bridge multilevel inverter; MPPT, maximum power point tracking; P&O, perturb and observer; STC, standard test condition; MNRE, Ministry of New and Renewable Energy; IGBT, insulated gate bipolar transistor; PWM, pulse width modulation; SVM, space vector modulation; CBPWM, carrier based pulse width modulation; SPWM, sinusoidal pulse width modulation; PD, phase disposition; PIV, peak inverse voltage; DF, distortion factor; FFT, fast Fourier transform; GW, giga-watt; DC, direct current; NPCMLI, neutral point clamped multilevel inverter; FCMLI, flying capacitor multilevel inverter; DLC, double level circuit; I-V, current-voltage; P-V, power–voltage; D, duty cycle; V_{out}, output voltage of boost converter; V_{in}, input output of boost converter; L, inductor; C, capacitor; CF, crest factor; RMS, root mean square; NMS, normalized mean square; MSO, mixed storage oscilloscope.

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different approach for different problems therefore leading to high development times. The theoretical studies are difficult and the analysis are usually empirical therefore it is difficult to state bounds on the quality of solution [7]. Therefore, Perturb and Observer MPPT technique utilized in this paper, overcomes these major drawbacks of metaheuristic algorithms.

The energy generated from solar PV is initially supplied to the domestic requirement and thereafter the remaining is fed to the grid through power electronic interfaces [8]. The generated voltage from solar PV is not meeting the requirement of grid voltage rating thereby DC-DC boost converter is mandatory for gaining the voltage rating [9]. Many topologies are developed under the category of non-isolated and isolated DC-DC converter. A comprehensive review on many new topologies for improving the voltage rating is reported in [10,11]. But the main drawback of these topologies are component count and converter cost. Also, many topologies requires high frequency transformer to gain the voltage rating. According to the standard of MIL-HDBK-217F, it is defined that the reliability varies depending on component count and therefore, topologies with lower number of components are preferred.

Inverter plays a major role in photovoltaic system to convert the generated DC voltage from panel to AC voltage, to be fed into the grid [12,13]. Three-level inverter is utilized for grid connection application [14,15] which produces higher total harmonic distortion which is suppressed by utilizing large size passive filters. Photovoltaic based multilevel inverter has gained attention lately for high voltage and high power application due to numerous advantages such as improved quality of output voltage, reduced total harmonic distortion, reduced size of passive filter and lower switching losses [16]. Neutral Point Clamped MLI, Flying Capacitor MLI and cascaded H-bridge MLI are the traditional single phase multilevel inverter topologies [17]. The device count increases with increase in the number of levels, therefore the researchers are focusing on new topological designs. Different multilevel inverter topologies are pointed out in [18,19–24] but they are not connected with PV system. In [25–28], traditional NPCMLI is integrated with photovoltaic system, but to maintain the constant voltage across each capacitor, an external controller is required. In [29], different types of CHBMLI are tested with PV panel but the drawback is more number of PV panels added in series or parallel connection to get the required voltage level. In [30], single phase transformer less PV based CHBMLI with different DC link voltage is discussed. Balancing of DC link capacitor is the major challenge when the topology is extended. In [31], sliding mode control based grid connected PV dual inverter is presented. But isolated transformers are needed to achieve the required output voltage level. Reduced switch multilevel inverter topology discussed in [32] and hybrid multilevel inverter topology in [33], are integrated with renewable power generation. In [33], large numbers of capacitors are required to maintain the required voltage level and in [32], the peak inverse voltage of the topology is high, whereas the proposed inverter of this paper requires lesser peak inverse voltage for higher number of levels which is proved in Section 4.2. In [34], a transformer based reduced switch multilevel inverter is connected with photovoltaic system. To generate the required output voltage level, each transformer secondary is cascaded. The utilization of transformer will increase cost and space. In [35,36], seven-level CHBMLI is integrated with the photovoltaic panel and it is tested with different irradiation condition.

This paper proposes a single phase multilevel inverter integrated with photovoltaic panel. A single phase MLI is a combination of conventional CHBMLI and a half bridge inverter circuit. The objective of the proposed MLI is to increase the output voltage level to nearly twice that of a conventional CHBMLI. A P&O MPPT algorithm with boost converter is utilized for replacing each DC input of proposed MLI. The utilization of separate DC-DC converter is by eliminating the extra controller to balance the DC link voltage, where proper selection of inductor and capacitor is important. The performance of PV based proposed MLI is compared with conventional PV based CHBMLI. The results are carried out for different irradiation and temperatures and also for step changes in climate conditions. The results are also compared with conventional CHBMLI for proving the effectiveness of proposed system results.

The remaining sections of this paper are organized as follows. Section 2 is the proposed PV integrated single phase multilevel inverter which includes modeling of PV, design of boost converter, P&O maximum power point tracking, cascaded H-bridge multilevel inverter without DLC circuit (conventional CHBMLI) and cascaded H-bridge multilevel inverter (proposed inverter). Section 3 describes the PWM technique for proposed MLI. Section 4 is the simulation results of CHBMLI without DLC and with DLC integrated with PV also analysis of switching losses, and theoretical calculation of total harmonic distortion. Section 5 presents the experimental results for proposed system and Section 6 ends with conclusion.

2. Proposed PV integrated single phase multilevel inverter

Fig. 1 shows the overall concept of proposed PV integrated single phase multilevel inverter configuration. It consists of PV panels with MPPT, boost converter, proposed multilevel inverter (CHBMLI with DLC circuit). The CHBMLI with DLC circuit provides 13-level output voltage with the help of 14 switches and 4 sources whereas conventional CHBMLI requires 24 switches and 6 sources for generating the same output voltage level. The proposed MLI can be extended to any number of levels based on the application and standards. The separate DC source of proposed multilevel inverter is replaced by separate PV panel with P&O MPPT and boost converter.

2.1. Modeling of PV

Fig. 2 shows the equivalent circuit of ideal PV cell in single diode model. The equivalent circuit consists of anti parallel diode with current source and series, parallel resistance [37]. The basic equation of ideal PV cell for generating I-V characteristics is as follows

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

The above equation does not support for generating I-V characteristics for PV array. PV array is formed by grouping of PV cell connected in series or parallel manner [37,38]. The solar cells connected in series provide higher output voltage whereas in parallel connection provides higher current. I-V characteristic depends on the value of series resistance, parallel resistance, temperature and irradiation [39]. Figs. 3 and 4 show I-V curve and P-V curve of 80 W photovoltaic panels respectively. Table 1 shows the different parameter values of 80 W PV panel. The mathematical formula for generating I-V characteristics are as follows

$$I = I_{PV} - I_o\left[\exp\left(\frac{V + R_sI}{aV_t}\right) - 1\right] - \frac{V + R_sI}{R_p}; V_t = \frac{V_skT}{q} \tag{2}$$

$$I_{PV} = (I_{PV,n} + K_I\Delta_t)\frac{G}{G_n} \tag{3}$$

$$I_o = \frac{I_{sc,n} + K_I\Delta_t}{\exp[(V_{oc,n} + K_V\Delta_t)/aV_t] - 1} \tag{4}$$