Electrical Power and Energy Systems 78 (2016) 165–173

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Modeling, control and analysis of cascaded inverter based grid-connected photovoltaic system

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ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form 21 November 2015
Accepted 25 November 2015
Available online 17 December 2015

Keywords:
Photovoltaic system
Cascaded two-level inverter
Vector control
Static compensator (STATCOM)

ABSTRACT

This paper proposes a vector controlled isolated source cascaded two-level inverter (CTLI), for grid connected photovoltaic (PV) system. The system is controlled to operate with variable solar irradiance, supplying different levels of active power. The PV systems are designed, modeled and tested with the proposed controller, to provide maximum power output. Additional operation as a reactive power supplier, in the absence of solar radiation, is also tested. A simple sinusoidal pulse width modulation (PWM) technique is used, instead of referred space vector PWM (SVPWM) technique, for the operation. Two different schemes have been considered to operate the inverter with equal and unequal DC-link voltages. The control scheme has been found working, for both active and reactive power supply in steady state and transient conditions. The power supplies of both the schemes are analyzed. The controller performance is found to be satisfactory for both the schemes to extract maximum power at the considered working conditions.

Introduction

The grid-connected PV system is one of the best options, for sustainable and independent energy generation practice. The power electronic technology plays an important role in the distributed generation and integration of renewable-energy sources into the electrical grid [1]. Many grids connected PV systems [26], use a three-phase voltage source inverter [2–4]. However, the conventional three-phase inverter produces three output voltage levels, and has poor spectral performance in lower switching frequency. The number of levels can improve the spectral performance at lower switching frequency. There are other attractive features, which make these kinds of power converters very interesting for the power industry, like (i) reduced current and voltage harmonics on the AC side, (ii) high-voltage capability, and (iii) low dv/dt [5–10]. Several multilevel topologies used for grid connection have been proposed in [5–9,11]. Multilevel converter structures have three major classifications; (i) neutral point clamped (NPC) or diode clamped, (ii) flying capacitor (FC) or capacitor clamped, and (iii) cascaded H-bridge (CHB) inverter, with isolated DC source [10,12]. The CHB inverter topology is very much popular because of its modular circuit layout [13]. The CHB topology requires the lesser number of DC-link capacitors than other topologies. The control of individual DC-link voltage of the capacitors is difficult [14]. The topology consists of two inverters connected to the open winding primary of a three-phase transformer.

In this work, the DC-link voltages of both the inverters are chosen to be in the order of battery voltage. The PV modules are connected at the DC-links of the CTLI. Accordingly, the PV modules are designed to deliver maximum power at that DC voltage, under rated Indian solar irradiance. A novel control strategy is developed to control the active power flow of the total DC-link voltage of two inverters. The circuit-based model of a PV array that can be implemented in any simulation environment is proposed in [15]. In the present study, single diode model of solar cell is used following the equations developed in [16].

DC/DC converters, connected to the DC-link capacitors, usually control the variations of output voltage of PV systems [5]. Various control strategies are available in literature to control the converters [5–10,14,17,18]. In [13], one control technique is proposed to keep the DC-link voltages constant for the isolated sources by balancing the active power flow. However, different level of DC-link voltages, which is favored because of certain harmonic reduction, and the maximum power generation by the different PV modules are beyond the scope of it. Accordingly, this paper proposes two schemes with equal and unequal voltage levels for the considered inverters for different solar irradiance level. The variation in solar irradiance level has to be introduced for checking the performance of the controller [20,27]. The PV modules of different voltage levels

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http://dx.doi.org/10.1016/j.ijepes.2015.11.092
0142-0615/

Nomenclature

V	solar cell terminal voltage [V]
I	solar cell terminal current [A]
I_{ph}	photo generated current [linear with irradiance]
I_s	saturation current due to diffusion mechanism
T	cell temperature [K]
K	Boltzmann's constant [$1.38 \times 10^{(-23)}$ J/K]
q	electron charge [$1.6 \times 10^{-19} C$]
n	diode quality factor [silicon diode $n = 2$]
R_s	cell series resistance [Ω]
R_{sh}	cell shunt resistance [Ω]
N_P	number of parallel cells
N_s	number of series cells
M	PV identical modules per string
N	identical PV strings
V_{dc}	DC-link voltage of the voltage source inverter (VSI)
V_{a1}, V_{b1}, V_{c1}	first inverter pole voltages
V_{a2}, V_{b2}, V_{c2}	second inverter pole voltages
$L-N$	line to neutral
V_q	q-component of the source voltage
V_d	d-component of the source voltage
e_d	d-components of the transformer output voltage
e_q	q-components of the transformer output voltage
i_d	d-components of the transformer output current
i_q	q-components of the transformer output current
V^*_{dc}	reference DC-link capacitor voltage of inverter
R_L	resistive load

are developed in this work. Two separate vector controller have been developed in this study for the two schemes. In both the cases, the proposed control technique maintains the total DC-link voltages of two inverters. Initially, the solar irradiance for the two inverters is considered to be same. Afterwards, the input is allowed to vary for each solar module separately. This variation in solar irradiance for the two PV modules of a single system is made to check even a difficult operating situation. The complete power circuit has been depicted in Fig. 1.

The paper is organized as follows: In the Section "Definition of the problem", definition of the problem is described. Section "Mat hematical model of a photovoltaic cell" presents a mathematical model for the photovoltaic cell. Section "Modeling of grid connected CTLI", illustrates the grid-connected CTLI topology and its modeling. The system description is given in Section "System description". Results followed by discussion are presented in Sections "Simulation result", "Reactive power control", and "Output power and efficiency of the schemes", respectively. Finally, the conclusions that have been drawn from the present work are summarized in Section "Harmonic analysis of the schemes".

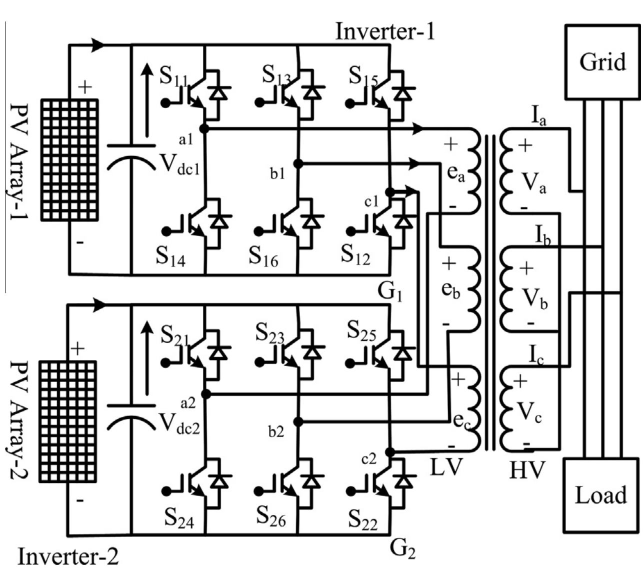

Fig. 1. Power circuit of the photovoltaic system with cascaded two-level inverter.

Definition of the problem

Two isolated PV sources are connected through the inverters as shown in Fig. 1. A novel control scheme is proposed so that the cascaded two-level inverter (CTLI) based system would work under variable solar irradiance levels and also in the absence of solar irradiance (as distributed static reactive power compensator). Two power schemes are studied, with the following nature.

I. Two inverters with same DC-link voltages
II. Two inverters with unequal DC-link voltages

To address the additional complexity of real-life variable solar irradiance, the inputs are considered to be different for two inverters as well. The solar irradiation is changed by ±17.133% in a step in the following manner.

(i) Solar irradiance of first inverter deviates as shown as Fig. 2(a).
(ii) Solar irradiance of second inverter deviates as shown as Fig. 2(b).

The step changes of the input to the power schemes are introduced in simulation environment following [20,27]. Since the changes in solar irradiance acts as an exogenous input disturbance, it is customary to consider this change as a step signal which signifies for a worst-case perturbation in input from the control engineering standpoint.

The modulation technique for the CTLI is tested with a simple sinusoidal PWM technique instead of generally preferred SVPWM modulation technique.

Finally, the overall system efficiency and total harmonic distortion (THD), to extract maximum power from the PV modules, has been investigated for both the power schemes with the considered solar irradiation variation.

Mathematical model of a photovoltaic cell

A mathematical description of the characteristic of PV cells is developed based on [16,21]. The characteristic equation is given in (1).

$$I = I_{ph} - I_s\left[\exp^{\frac{q(V+IR_s)}{nKT}} - 1\right] - \frac{V + R_s I}{R_{sh}} \tag{1}$$

The equivalent circuit, determined from the equation, is presented in Fig. 3.