Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 84 (2010) 1310–1317
SOLAR ENERGY
www.elsevier.com/locate/solener

Photovoltaic solar system connected to the electric power grid operating as active power generator and reactive power compensator

Fabio L. Albuquerque *, Adélio J. Moraes, Geraldo C. Guimarães, Sérgio M.R. Sanhueza, Alexandre R. Vaz

Universidade Federal de Uberlândia, Uberlândia-MG, CEP 38400-902, Brazil

Received 14 July 2009; received in revised form 3 April 2010; accepted 15 April 2010
Available online 12 May 2010

Communicated by: Associate Editor Igor Tyukhov

Abstract

In the case of photovoltaic (PV) systems acting as distributed generation (DG) systems, the DC energy that is produced is fed to the grid through the power-conditioning unit (inverter). The majority of contemporary inverters used in DG systems are current source inverters (CSI) operating at unity power factor. If, however, we assume that voltage source inverters (VSI) can replace CSIs, we can generate reactive power proportionally to the remaining unused capacity at any given time. According to the theory of instantaneous power, the inverter reactive power can be regulated by changing the amplitude of its output voltage. In addition, the inverter active power can be adjusted by modifying the phase angle of its output voltage. Based on such theory, both the active power supply and the reactive power compensation (RPC) can be carried out simultaneously. When the insolation is weak or the PV modules are inoperative at night, the RPC feature of a PV system can still be used to improve the inverter utilisation factor. Some MATLAB simulation results are included here to show the feasibility of the method.

Keywords: Photovoltaic solar systems; Distributed generation; Reactive power; Active power

1. Introduction

At present, a photovoltaic (PV) system or plant PV is commonly connected to the electrical grid as a distributed generation (DG) system, especially in developed regions such as, for example, Japan, the USA, and Europe (Erge et al., 2001; Schoen, 2001; Wiemken et al., 2001). Normally, this PV system is strategically placed near consumption points where the delivery of electrical energy is needed, which can relieve generation, transmission and distribution systems. Consequently, such a strategic location can delay the need for new investments and improve the load curve and voltage profile of the feeder, reducing the level of grid and transformer loadings and reduction electrical losses (Hoff et al., 1996; Ackermann, 2001; Salmam, 2001; Hoff and Shugar, 1995; Conti et al., 2003), as well as bring environmental benefits by avoiding the emission of pollution (Krauter and Ruther, 2004; Spiegel et al., 2000). Special attention should be paid to Germany, where there are programs that aim to install 100,000 solar roofs and PV systems in schools. These programs are supported by the federal government and by local energy companies (Erge et al., 2001; Decker and Jahn, 1997).

Utilisation of an inverter is needed to operate a PV system connected to the electrical grid for the conversion of direct current (DC) to alternating current (AC). It is important to mention that the majority of inverters that are currently used to connect the PV system to the electrical power

* Corresponding author. Tel.: +34 3239 4166.
E-mail addresses: fabiolima@etfto.gov.br (F.L. Albuquerque), ajmoraes@ufu.br (A.J. Moraes), gcaixeta@ufu.br (G.C. Guimarães), sergiorivera@etfto.gov.br (S.M.R. Sanhueza), alexandrevaz@hotmail.com (A.R. Vaz).

0038-092X/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2010.04.011

grid are current source inverters (CSI) operating with a unity power factor, which implies that they are capable of providing only active power to the grid system. Thus, the reactive power required by the local loads will continue to be supplied by a capacitor bank connected to the primary distribution system or to the substation. Therefore, when the insolation is weak or during the night, such PVs systems lose their power-generating capacities and become useless; all loads must be fed directly by the electrical grid.

However, if the voltage source inverter (VSI) is used instead of the CSI, reactive power can be generated and absorbed using the available capacity of the inverter at a specific moment in accordance with the demand of the electrical grid (Begović et al., 2001; Hassaine et al., 2009; Mekhilef and Rahim, 2004; Yu et al., 2005). Thus, in this work, the inverter connected to the electrical grid simultaneously supplies the active power generated by the PV system and feeds or consumes the reactive power in accordance with the necessity of the distribution grid and the availability of the PV power. When the insolation is weak or the PV system is turned off during the night, the reactive power compensation (RPC) function is used. This extra function increases the availability of and improves the energy quality of the grid because there is local power compensation control. Some theoretical analysis and simulation results using a VSI inverter will follow to confirm the methodology proposed here.

2. Operation principles

When talking about power generation and consumption, the analysis of an inverter can be performed analogous to that of a synchronous machine connected to an infinity bus, but the inverter dynamics are faster due to the absence of rotor inertia. Conversely, the necessity of imposing on the inverter a behaviour comparable to the synchronous machine, it makes the inverter control dependent on the feedback signal from the grid voltage. Fig. 1 shows the single-phase inverter connected to the grid.

In contrast with synchronous machines, there is a relationship between neither the phase shifts of generator voltages and the active power nor between the output voltage amplitude and the reactive power of power inverters. Thus, to connect an inverter to an infinity bus, it is necessary that these linkages be created by the control system so that stable operation can be achieved.

The active power P and reactive power Q carried by the electrical grid can be calculated through Eqs. (1) and (2) (Stevenson, 1982).

$$P = \frac{V_i V_s}{2\pi f L_C} \sin\delta = P_{MAX} \sin\delta \quad (1)$$

$$Q = \frac{V_i^2}{2\pi f L_C} - \frac{V_i V_s}{2\pi f L_C} \cos\delta \quad (2)$$

where V_i = voltage on the terminals of the inverters, V_s = voltage of the electrical grid, L_C = inductance of the coupling inductor, δ = phase difference between voltages V_i and V_s, f = frequency of the system.

To have reactive energy transfer between the inverter and the electrical grid, it is necessary to provide an amplitude difference between their voltages. If the inverter voltage V_i is greater than the electrical grid voltage V_s, but they are in phase, the inverter supplies only reactive power to the grid (capacitive mode). Conversely, if voltage V_i is smaller than voltage V_s but still in phase, the inverter absorbs reactive power from the grid (inductive mode).

If the inverter has energy storage equipment (battery, fuel cell, or PV system) on the DC side, it can carry out active power exchange between the inverter and the electrical grid. The active power exchange can be controlled by the phase shift between voltages V_i and V_s. If it is thus desirable to absorb active power from the grid, the output voltage is generated with a delay and with the same magnitude as the grid voltage. This defines the direction of active power flow as being from the grid to the inverter. The inverter can also provide active power to the grid if the inverter output voltage has the same magnitude as the grid voltage but is advanced in phase. This operation is possible because there is a suitable energy storage apparatus on the DC side. So, when the voltage V_i is delayed or advanced relative to V_s (by an angle smaller than 90°), and with the same voltage magnitude, it provides active power absorption or generation, respectively. The analysis is

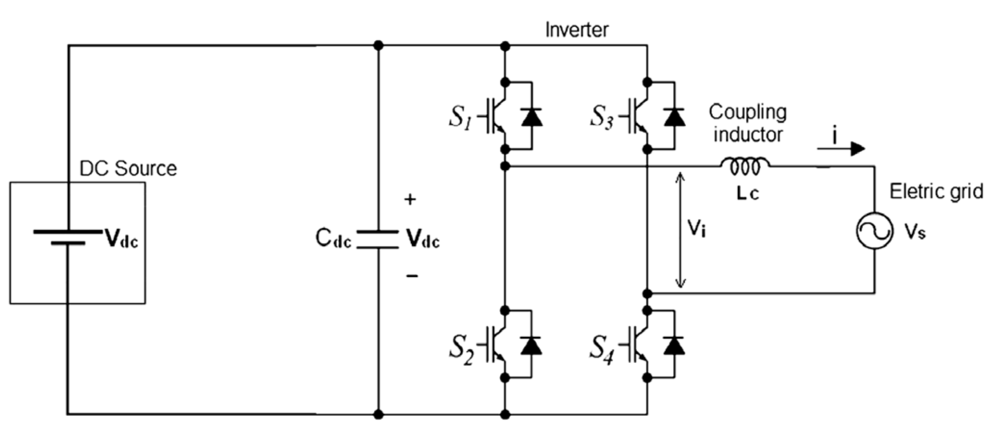

Fig. 1. General single-phase inverter system connected to the electrical power grid.