Electrical Power and Energy Systems 82 (2016) 314–330

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A new backstepping finite time sliding mode control of grid connected PV system using multivariable dynamic VSC model

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ARTICLE INFO

Article history:
Received 26 May 2015
Received in revised form 17 March 2016
Accepted 20 March 2016
Available online 29 March 2016

Keywords:
Dynamic active and reactive power model
Photovoltaic (PV) array
Incremental conductance method (INC.)
Voltage source converter (VSC)
Lyapunov based adaptive sliding mode control (LYPSM)
Backstepping finite time fast sliding mode (BFTSM)

ABSTRACT

This paper presents independent active and reactive power management of a three-phase grid-connected photovoltaic (PV) generation system using a new nonlinear control approach for the voltage source converter (VSC). Instead of controlling the direct and quadrature-axis currents of the VSC, the instantaneous active and reactive powers are used as error estimation parameters. This mode of control dispenses the unmodelled dynamics of the VSC phase-locked loop system and produces a robust control for the active–reactive power, and dc voltage excursions. This approach reduces computational time as well as complexity by avoiding unnecessary PLL phase calculation in the beginning. However, the PLL is used only to obtain the frequency component needed to generate the PWM signal. Further to improve the stability and robust tracking of the grid connected PV array, backstepping finite time fast sliding mode (BFTSM) control strategy is presented in this paper. The proposed controller offers invariant stability to modeling uncertainties due to converter parameter changes, changes in system frequency and exogenous inputs. Also the finite time sliding mode control offers an important tool for designing continuous finite time control laws. Comprehensive computer simulations are carried out in MATLAB/Simulink to verify the proposed control scheme under several system disturbances like changes in solar insolation, changes in local load, converter parametric changes, and faults on the converter and inverter buses, and partial shading condition of PV array. EMTDC/PSCAD model is established as confirmative study.

Introduction

The recent years exhibit research trends in renewable energy management, self-sufficient local area micro-generation and power flow analysis of distributed generation sources. The huge increase of grid connected PV generation system can pose serious challenges to maintain grid stability, power quality, power mismatch, power control, energy management and also efficient protection tasks, etc. [1,2]. Various power flow control strategies for three-phase grid connected PV systems have been reported in the literature [3–6]. In [6], dynamic modeling of PV systems has been carried out for designing appropriate interfacing circuits and controllers for practical PV systems and to investigate PV transient responses with change in solar irradiance and operating temperature. The connection of the PV array to the grid is usually made with a voltage source converter (VSC), and it may include intermediate dc–dc converter, a transformer, or even both. It has been reported that high bandwidth grid active and reactive power control is achieved by directly controlling the currents of the VSC. Most of the controllers belong to either PI controllers or hysteresis band type controllers. The controllers are implemented in synchronously rotating reference d–q frame using PI controller or stationary *abc* reference frame using proportional resonant (PR) controller. A predictive controller based current control scheme implemented in synchronously rotating reference frame is proposed in [7]. Further the PI controllers are designed by trial and error and their performance deteriorates with the changing of the operating conditions. Besides the PI controller, several other linear and nonlinear controllers have been reported for active and reactive power flow control in the PV inverters [8–10] using *dq* current components as dynamic variables. To reduce the degree of nonlinearities in current control models due to the use of dynamic phase-locked loop (PLL), a new control strategy has been adopted in [11] by using the instantaneous active and reactive power components as dynamic variables in a stationary frame of reference. By avoiding the unnecessary PLL frequency component calculation at the beginning of control design, a reduced computational elapsed time is achieved. this supports the fact that the proposed P–Q based dynamic model is effective to achieve a less complex VSC model in terms of computational complexity.

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http://dx.doi.org/10.1016/j.ijepes.2016.03.034
0142-0615/

In earlier studies active and reactive power flow at PCC (point of common coupling) are determined as error estimation variables and this requires the availability of active and reactive power reference values. As assumptions have been made for swing bus voltage d–q components, the reactive power reference from VSC to PCC is obtained negligible. But the active power from VSC to grid is dependent on the MPPT (maximum power point tracking) control adopted for the PV arrays in the system. As specified in [12–15], the above mentioned control does not have any interaction with MPPT control while providing reference signals for the grid interactive PV system. A feedback linearization approach is presented in [16] to overcome this problem by providing reactive power compensation and active power control via MPPT. However, the feedback linearization approach does not take into account the various uncertainties that might arise for a grid connected PV array during changes in irradiance and PV cell temperature and will affect the control.

Thus in this paper after establishing the nonlinear mathematical model of the PV array with MPPT control and the VSC system, a small signal stability framework is presented which provides insight to the nature of the multivariable VSC dynamics for two independent single input single output (SISO) systems with linear (PI) control gains, which is required for stability against small changes. For large changes in the operating conditions of the PV power system a nonlinear control using an adaptive sliding mode strategy is derived for the converter station. The Lyapunov function based controller (LYPSM) provides a chattering free sliding mode characteristic that has the ability to take care of the modeling uncertainties, and the disturbances. Further the sliding mode strategy is made adaptive [10] to provide a more robust control of the 3-phase grid connected PV array. Adaptive backstepping control method with bounded uncertainties for nonlinear system has been introduced [19,20]. Backstepping control for VSC-HVDC system has been implemented [21]. An adaptive backstepping approach with line impedances as uncertain parameters is being discussed in terms of synchronous frame currents in both side VSC and DC link. The control approach contributes significant improvement in dynamic behavior of the VSC-HVDC system but still lacking in fast tracking error, robustness. In this paper a LYPSM control is treated as conventional sliding control approach. A Backstepping finite time fast sliding mode (BFTSM) is designed using adaptive backstepping method on a nonlinear sliding surface based on the Lyapunov's direct stability theorem that guarantees fast response and the tracking error to reach the sliding surface in finite time. The proposed nonlinear control achieves active and reactive power management at the inverter side of the VSC with simultaneous stabilization of the dc link voltage. In addition to it, for load changes at the PCC, the frequency is computed with the help of PLL and a frequency controller can be incorporated. In this paper several computer simulations are carried out in different operating conditions of the two-area power system and results are presented to commemorate the robustness of the designed controller.

This paper is organized in five sections. After the introduction in Section "Introduction", Section "Photovoltaic system design" presents a detailed PV system model followed by dynamic model in Section "Dynamic model of VSC" and the small signal stability analysis of the PI control of VSC in Section "*P–Q* Controller design". Also the BFTSM controller of VSC model is discussed in Section "*P–Q* Controller design". Several test cases and the simulation results that include faults, changes in solar insolation, converter parametric changes, islanding condition, partial shading condition of PV array etc. are presented in Section "System study and simulation results" to highlight the superior performance of the new approach. Lastly concluding remarks and future scopes of work are given in Section "*P–Q* Controller design".

Photovoltaic system design

Mathematical model of PV array

The elemental unit of PV system is PV cell, irrespective of the utilization. The output voltage of a single PV cell is low (around 0.5 volts). Thus in pragmatic application, these basic units are combined in number of parallel cells (N_p) and series cells (N_s) to obtain the output current (I_{pv}) function of the PV array, as mentioned:

$$I_{pv} = N_p[I_{ph} - I_{rs}(\exp^{\alpha V p v} - 1)] \tag{1}$$

where $\alpha = \frac{q}{N_s \times T \times k \times a}$ and V_{pv} is voltage at PV array output terminal. $q = 1.602 \times 10^{-19}$ C, is charge of an electron; $k = 1.38 \times 10^{-23}$ J/K, is Boltzmann constant; a is ideality factor of diode equation. I_{ph} is photo current, generated by photon insolation is derived as:

$$I_{ph} = 0.01 \times G \times [I_{sc} + k_i(T^* - T)] \tag{2}$$

where G is solar insolation in Watt/m^2; I_{sc} is short circuit current of the of PV cell; k_i=0.015, is short circuit current temperature coefficient as mentioned in datasheet of the PV module. T^* and T is temperature at Standard test condition (STC) and working temperature of the cell, respectively. The reverse saturation current (I_{rs}) of the diode from the equivalent circuit of PV cell is estimated as shown:

$$I_{rs} = I_{rr}\left(\frac{T}{T^*}\right)^2 \times \exp\left[\frac{q \times E_g}{k \times a}\left(\frac{1}{T} - \frac{1}{T^*}\right)\right] \tag{3}$$

where E_g is band gap energy of the semiconductor material of the cell.

MPP tracking with incremental conductance control with variable step size

The output power of the PV array is calculated as $P_{pv} = I_{pv} \times V_{pv}$ and the nature of the power vs. voltage or current vs. voltage graph is highly nonlinear in nature. Thus maximum power point tracking algorithms are used for extracting maximum power from the PV module and transferring that power to the load. The proposed system model is employing a MPPT scheme called Incremental Conductance (INC) with variable step size as obtained in Eqs. (4) and (5). It is well known that the voltage and current output of the PV panel vary with the changes of sun's irradiation and temperature. Therefore, those two parameters are acquired as input from MPPT scheme to harness maximum power from the PV panel. I_{pv} and V_{pv} are measured and are used as inputs to the MPPT algorithm. The INC algorithm is based on the fact that the derivative of PV power by the voltage is equal to zero. Accordingly, at the maximum power point:

$$\frac{dP_{pv}}{dV_{pv}} = N_p\left[I_{ph} - I_{rs}\left(V_{pv} \times \exp^{\alpha V_{pv}} + \exp^{\alpha V_{pv}} - 1\right)\right] = 0 \tag{4}$$

The step size (Δv) is reduced and accurate the tracking as it reaches nearer to the MPP point:

$$\Delta v = N * abs(dP_{pv}/dV_{pv}) \tag{5}$$

The proposed MPPT technique is equipped with partial shaded condition handling capacity by means of a sorting algorithm, each time it receives a $dP_{pv}/dV_{pv} = 0$ condition. Also during partial shading condition, the PV system shows P–V/I–V characteristic with multiple peaks. To determine the global peak among all other local peaks, the proposed algorithm is efficient as described in Section "Case 2: Partial shaded condition".

The studied system is modeled for a power rating of 10 kW and voltage rating of 115 V, 50 Hz in MATLAB *Script* editor where STC (G = 1000 W/m^2 and T = 25 °C) will generate $P_{pv} = 1.0425$ p.u and