Solar Energy 173 (2018) 804–813

Contents lists available at ScienceDirect

Solar Energy

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

Control oftransformerless grid-connected PV system using average models of power electronics converters with MATLAB/Simulink

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ARTICLE INFO

Keywords:
PV
Grid
MPPT
PLL
Average model
Decoupled Watt-Var Control

ABSTRACT

This paper presents the analysis, modeling and control of a grid connected photovoltaic (PV) system supplying two local loads. For this purpose, the average models of both boost converter and three-phase voltage source inverter (3-ph VSI) are used. Their advantage in term of computational speed allows simplifying and accelerating the simulation in order to develop their control laws. A Fractional Open Circuit Voltage (FOCV) algorithm based Maximum Power Point Tracking (MPPT) control technique is modified and combined with a DC-DC boost converter. The Watt-Var control approach is presented for the 3-ph VSI control. The Both proposed control algorithms are thereafter validated in detailed (switching) models. The proposed model is implemented in the MATLAB/Simulink software and simulation studies are presented. The simulation results show the advantage of using Power Electronics Converters (PEC) in their average versions. They also demonstrate the high performance and feasibility of the proposed system with its control strategy.

1. Introduction

The worldwide electrical energy consumption is increasing exponentially. To meet this rising demand, it is necessary to install more power plants. But, since fossil fuels reserves are finite and it's just a matter of time before they will run out, needless to mention their - contribution in global warming, many countries are now examining their national energy policies and looking to embrace other alternatives (Adaramola and Vågnes, 2015). Renewable energies are among the energy sources that offer another way to avoid this fossil energy deadline. They are also expected to play an important role as a clean electricity power source in the future energy demands (Vijayraol et al., 2013; Marouani and Mami, 2010). Among this various renewable energy sources, PV power generation systems which are the most used. One of the most important applications is the Grid Connected PV system (Gabler, 2001).

A typical solution would be to develop a residential PV power supply system within the consumer reach. This system can also contribute in the power system stability and power quality (Hamrouni and Chérif, 2007).

However, the grid-connected PV application presents generally two problems, the first problem is the achieving the MPPT controller in order to maximize the delivered power regardless of the climatic conditions or the load variation (Roy and Mahmud, 2017; Yang and Zhao, 2011; Marouani and Mami, 2010). The second problem is the synchronization with the utility grid (Zahoor et al., 2014; Kalitjuka, 2011; Hamrouni and Chérif, 2007).

Considerable efforts have been made into the control of these systems. The most common control strategies structures applied to this decentralized power generator is based on Power-Angle Control (PAC) which is also called Voltage-Angle Control (VAC) (Kalitjuka, 2011), Voltage Oriented Control (VOC) (Vijayraol et al., 2013; Marouani and Mami, 2010), P-Q Control (Liu et al., 2015; Rey-Boué et al., 2012; Li et al., 2011), or Decoupled Current Control (Zahoor et al., 2014; Milosevic et al., 2006). Another Active Power Control using a robust nonlinear adaptive backstepping approach has been discussed in Roy and Mahmud (2017). But, these researches have been done using PEC regardless of their models type (detailed or averaged) (Channegowda et al., 2014; Hamrouni and Chérif, 2007). The switching model (detailed model) is modeled with IGBT/diode pairs controlled by pulses, produced by a Pulse Width Modulation (PWM) generator (Molina and Mercado, 2008; Ye et al., 2004). This model provides the most accurate simulation results, but takes a long simulation time (Ye et al., 2004). Further, it cannot give satisfaction for the analysis of small-signal due to its discrete behavior (Hamrouni and Chérif, 2007; Ye et al., 2004). While, Average value modeling further simplifies PEC representation by neglecting the switching effects (Khan et al., 2016; Channegowda et al., 2014). Indeed, the average model is modeled using a switching-

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https://doi.org/10.1016/j.solener.2018.08.012
Received 5 February 2018; Received in revised form 2 August 2018; Accepted 4 August 2018
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Nomenclature

Terminology

PV	Photovoltaic
VSI	Voltage Source Inverter
FOCV	Fractional Open Circuit Voltage
MPPT	Maximum Power Point Tracking
OP	Operating Point
MPP	Maximum Power Point
PAC	Phase Angle Control
VOC	Voltage Oriented Control
PWM	Pulse Width Modulation
PI	Proportional Integral
PEC	Power Electronics Converters
Mosfet	Metal Oxide Semiconductor Field Effect Transistor
IGBT	Insulated-Gate Bipolar Transistor
DSP	Digital Signal Processor
DCM	Discontinuous Conduction Mode
STC	Standard Test Conditions
TF	Transfer Function
PCC	Point of Common Coupling
PLL	Phase Locked Loop
PVG	Photovoltaic Generator
SF	Switching Function

Symbols

KC200GT	Kyocera, 200 W-16 V Nominal Solar Module
L	Output Filter
$\mathbf{u_{abc}} = \{\mathbf{u_a}, \mathbf{u_b}, \mathbf{u_c}\}$	3-ph controlled output VSI Voltages
$\mathbf{v_{abc}} = \{\mathbf{v_a}, \mathbf{v_b}, \mathbf{v_c}\}$	3-ph Grid Voltages measured at PCC
$\mathbf{i_{abc}} = \{\mathbf{i_a}, \mathbf{i_b}, \mathbf{i_c}\}$	3-ph grid currents
$\mathbf{u_{dq}} = \{\mathbf{u_d}, \mathbf{u_q}\}$	Direct and Quadrature Components of space vector (u) expressed in park reference frame
$\mathbf{v_{dq}} = \{\mathbf{v_d}, \mathbf{v_q}\}$	Direct and Quadrature Components of space vector (v) expressed in park reference frame
$\mathbf{i_{dq}} = \{\mathbf{i_d}, \mathbf{i_q}\}$	Direct and Quadrature Components of space vector (i) expressed in park reference frame
$\mathbf{v_{\alpha\beta}} = \{\mathbf{v_\alpha}, \mathbf{v_\beta}\}$	Alpha and beta Components of space vector (v) expressed into orthogonal stationary reference frame
$\mathbf{u_{abc\_ref}}$	Voltages references for VSI Control
VLL	Line to Line RMS Voltage
$\mathbf{i_{dref}}$	Direct current reference
$\mathbf{i_{qref}}$	Quadrature current reference
$\mathbf{P_{max}}$	Maximum Power
P	Active Power
Q	Reactive Power
W	DC Electrical Energy
$\mathbf{P_{dc}}$	DC Electrical Power
f	Frequency
ω_n	Nominal angular frequency
$\mathbf{v_d^*}$	Direct component Voltage Reference
ω_i	Cutoff angular frequency
ω_0	Radian frequency of the grid voltage
m	Modulation Index
Ph	Phase
$\mathbf{V_{dc}}$	DC Bus Voltage
$\mathbf{V_{dc\_ref}}$	DC Bus Voltage reference
d	Duty Cycle
θ	Actual phase angle of grid first phase voltage
θ'	Estimated phase angle detected by the PLL
$\mathbf{T_{\alpha\beta}}$	Clarke transform
$\mathbf{T_{dq}}$	Park transform
ξ	Damping coefficient
$\mathbf{v_a}$	Grid first phase voltage
$\mathbf{v_o}$	Output Voltage of the boost converter
$\mathbf{v_{in}}$	Input Voltage of the boost converter
$\mathbf{V_{vp}}$	Voltage at Operating point (OP)
$\mathbf{V_{mpp}}$	Voltage at MPP
$\mathbf{V_{oc}}$	Open Circuit Voltage
$\mathbf{V_{oc\_ref}}$	Open Circuit Voltage Reference
$\mathbf{v_m}$	Grid voltage amplitude
$\mathbf{N_x}$	Serial cells of the pilot PV module
$\mathbf{N_s}$	Serial cells of the PV module
$\mathbf{n_s}$	Number of the PV module
K	Constant of proportionality
C	Capacitance
G	Irradiation
Ts	Sample Time
S	Laplace Operator
$\mathbf{K_p}$	Proportional gain of current loop control
$\mathbf{K_i}$	Integral gain of current loop control
$\mathbf{Kp_2}$	Proportional gain of the DC bus voltage loop control
$\mathbf{Ki_2}$	Integral gain of the DC bus voltage loop control
$\mathbf{P_{ref}}$	Active power reference
$\mathbf{Q_{ref}}$	Reactive power reference

function (SF) directly controlled by reference voltage (u_{ref}) or by duty-cycle (d) ($0 < d < 1$). Therefore, in average model case, there is no need to implement a PWM generator block that requires high switching frequency (f). That's why this model provides faster simulations than the detailed model (Channegowda et al., 2014). In addition, these models are also useful to predict converter steady-state characteristics and small-signal dynamics in discontinuous conduction mode (DCM) (Menegaz et al., 1999). Also, and in spite of its disadvantages, the average model remains often useful before the final control design (Hamrouni and Chérif, 2007). It is considered a good compromise between complexity, computation time and acceptable accuracy for system simulation (Merdassi et al., 2011; Allain et al., 2009).

Due to these advantages, the average models of the both PEC are used in this article in order to accelerate the simulation.

This paper describes the dynamic performances of a residential PV system connected to a small distribution grid and feeding two local loads. This PV system integrates a transformerless 3-ph VSI (Boukezata et al., 2014) of less than 10 kW, which meets the most consumers load requirement. The energy produced by the PV Generator (PVG) is directly consumed by these two local loads. Eventual extra production is injected into the grid which is assumed as large balanced power source and that can supplement the energy supply coming from PVG.

Furthermore, since these PV systems directly feed their solar energy into the grid, expensive storage batteries are not necessary, and can be removed from most PV systems connected to the grid. (Adaramola and Vågnes, 2015; Rekioua and Matagne, 2012; Yang and Zhao, 2011). Also, as this kind of PV systems is continually connected to the grid, solar energy consumption and solar panel sizing calculations are not required.

After having tested under MATLAB/Simulink some control strategies using the advantage of this models version, the decoupled active and reactive powers (Watt-Var) control approach (Mahamat et al., 2016; Molina and Mercado, 2008; Hamrouni and Chérif, 2007) is opted for the 3-ph VSI. This approach aims to inject maximum active power and zero reactive power to the utility grid in order to achieve a unity power factor (Roy and Mahmud, 2017; Bullich-Massaguá et al., 2017; Hassaine et al., 2014). Further, this control allows to the 3-ph VSI to keep a constant DC bus voltage and to transform it to AC voltage

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