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FPGA-based real time simulation and control of grid-connected photovoltaic systems

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ABSTRACT

Nowadays, FPGA devices are widely used to build control platforms in various fields of real time applications such as wireless telecommunications, image and signal processing, robotics and renewable energy systems. In grid-connected photovoltaic (PV) systems, an effective control strategy is needed for an efficiently use of solar energy as well as for energy supplies optimization. This paper presents an investigation, modelling and FPGA based digital controller design of a two-stage grid connected photovoltaic (GCPV) system. The basic idea of the proposed control structure is to operate the PV system as an active power generator and reactive power regulator. Firstly, a comprehensive study of dynamic behaviour of a two-stage GCPV system using Matlab/Simulink was presented. Subsequently, a digital circuit design of Incremental Conductance (IncCond) algorithm and decoupled active–reactive power control algorithm is carried out using the Hardware Description Language (VHDL). The simulation results confirm the accuracy of the adopted control strategy as well as the feasibility of the overall FPGA based control circuit.

1. Introduction

The photovoltaic generation system is one of the most promising renewable energy sources, as it has the advantages of being safe, inexhaustible, pollution free and requiring little maintenance. The photovoltaic (PV) systems are used today in many applications which can be classified into two main categories: the stand alone PV system and the grid connected PV system. In remote rural areas where the grid connection is impossible, the stand-alone PV systems are used with a battery bank for the energy storage. On the other hand, to answer the need for alternative energy, the grid connected PV systems are used. In this kind of system, the PV panels are connected to the utility grid without the employ of battery bank such that the available PV power is delivered to the electric grid.

The amount of power generated by photovoltaic panel depends mostly on the atmospheric conditions (solar irradiation and air temperature). So to reach the maximum PV generation point for a given operating conditions, a Maximum Power Point Tracker (MPPT) is used enabling the control of PV module's operating point. A large variety of MPPT methods have been proposed in the literature in order to improve the solar panel efficiency, such as: Hill-Climbing method [1], Perturb & Observe method and its improved version [2], incremental conductance method [3], and other improved methods can be find in [4,5].

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Nomenclature

PV	photovoltaic
DC	direct current
AC	alternative current
D	duty cycle
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
GCPV	grid connected photovoltaic system
DSP	Digital Signal Processor
FPGA	field programmable gate array
SPWM	Sinusoidal Pulse Width Modulation
PF	power factor
PI	proportional integral
PLL	phase looked loop
VCO	Voltage Controlled Oscillator
LF	loop filter
PD	Phase Detector
IncCond	Incremental Conduction
VSI	voltage source inverter
THD	total harmonic distortion
I_d	direct component of inverter current
I_q	quadrature component of inverter current.
I_{grid}	grid current
I_{ref}	reference grid current

The most commonly used of the abovementioned methods is the Incremental Conductance (IncCond) one. In this algorithm, the Maximum Power Point (MPP) is periodically determined by comparing the incremental conductance with the instantaneous conductance based on the PV panel's voltage and current information as reported in [3,6]. Usually, the MPPT controller is associated with a DC–DC or DC–AC power converters.

On the other hand, to be able to connect a photovoltaic generator to an electrical grid, it is vital that the PV system meets the power grid requirements as well as the power quality standards. Typically, the single-phase voltage-source inverters (VSI) are widely used in the small-scale PV power generation systems for interfacing with the single-phase grid. The DC energy produced by PV panel is fed to the utility line through VSI such that its main target is to process the maximum PV power and to inject an alternative current into the utility line. Thus, the overall efficiency of the GCPV system depends on the efficiency of DC into AC power conversion.

Actually, different power management configurations for grid connected PV systems interface exist such as: the single-stage and the two-stage structures. The number of stages involved in the grid connected PV system is an important issue, since it determines the overall efficiency, reliability and control complexity in such systems. In a dual-stage GCPV system, the functions of the DC–DC and DC–AC power converters are independent that makes the global control task easier than the one-stage configuration. However, the overall efficiency of the inverter decreases due to the connection of two converters.

In order to achieve an efficient energy generation system, the grid connected PV inverter is controlled so as to inject a pure sinusoidal current (AC) synchronized with the utility voltage. The power conditioning interface between the PV generator and the grid can become more efficient by choosing an appropriate command strategy. Usually, the control structure of VSI comprises an internal current loop that affects significantly the system dynamic performances. Enabling the power quality control, several current control strategies have been proposed in the literature [7–10] such as hysteresis current control (CHC), predictive direct control (PDC), dead-band based controller, and voltage oriented control (VOC) with PWM modulator.

To realize prototypes and to test the control strategies of energy generation systems, the trend of researches now is to use digital implementation which provides more improvements over their analogue counterparts [11–14]. Traditionally, the control algorithms of power converters are designed with Digital Signal Processors (DSPs) and microcontrollers. Unfortunately, Microcontrollers and DSPs suffer from difficulties with control systems that require high operating and handling speed. Also, in the case of complex control structures, programming DSP or microcontroller becomes time-consuming task resulting in poor performances. However, recent advances in FPGA technologies with field reprogramming ability, fast computation capability, and short time-to market make it's an attractive solution for digital implementation of sophisticated control algorithms in real time application. In comparison to DSP implementations, the field-programmable gate arrays FPGAs provide higher degree of flexibility in case of on-line changes that DSP chips can offer. Therefore, the advantage of using a FPGA rather than the cheaper microcontroller lies in the fact of reaching very high sampling frequencies, ensuring better performances with low power consumption. Furthermore, additional design functionalities can be incorporated into