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Backstepping Control of Photovoltaic-Grid Hybrid Power Feed Water Pump

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Abstract: We are considering the problem a controlling of photovoltaic-grid pumping system. The system consists of a PV panel, a PWM AC/DC rectifier connected to a single-phase grid, an association of a PWM DC/AC inverter - squirrel cage induction motor, and a centrifugal water pump. The control objectives are fourfold: (i) forcing the pump water flow rate to track any reference signal (ii) regulating the rotor flux norm to its nominal value (iii) regulating the DC Link voltage to a reference value to meet the maximum power point tracking (MPPT), (iv) and the power factor correction (PFC). To meet these control objectives, we first develop a nonlinear model of the whole controlled system in the Park-coordinates. Then, a multi-loop nonlinear controller is synthesized using the backstepping design technique. In addition to closed-loop global asymptotic stability, it is proved that all control objectives (water flow rate tracking, rotor flux regulation, DC link voltage regulation and unitary power factor) are asymptotically achieved.

Keywords: Photovoltaic arrays, AC/DC rectifier, Centrifugal pump, MPPT, nonlinear control, backstepping technique, Lyapunov stability.

1. INTRODUCTION

Solar water pumping minimizes the dependence on diesel, gas or coal based electricity. The use of diesel or propane based water pumping systems require not only expensive fuels, but also create noise and air pollution. Solar pumping systems are environment friendly and require low maintenance with no fuel cost Chandel *et al.* (2015)).

Several solar pumping structures have been proposed in the literature. In Rahrah *et al.* (2015) and Correa *et al.* (2008) the photovoltaic pumping system in standalone mode is studied induction machine entraining centrifugal pump. Furthermore in Rahrah *et al.* (2015) the chopper to extract maximum output power from photovoltaic generator and battery for storage are used. In Caracas *et al.* (2014) a PV water pumping converter and treatment systems without using storage elements was presented. Using hybrid PV-grid and elimination of storage unit to fed pumping system, reduces the physical size of PV panel area required for a given output, improves power yield, overall efficiency of the system and return on investment Rahul *et al.* (2016).

The energy extracted from a PV module is dependent on climatic conditions. Several maximum output power tracking methods have been proposed in the literature. In Rahrah *et al.* (2015), Perturbation and Observation (P&O), Fuzzy Logic Controller (FLC) and Neuro-Fuzzy algorithm (NF) have been presented. In Marouani *et al.* (2014), a Maximum Power Point Tracker (MPPT) has been presented and applied to a PV water-pumping system. A fuzzy logic MPPT was developed in Aashoor *et al.* (2013).

In this paper, a nonlinear control of photovoltaic-grid pumping system is presented. The controlled system consists, on one hand, of a combination of AC/ DC rectifier connected to PV generator (PVG), and, a on the other hand, an association "DC/AC inverter - squierel cage induction motor"driving a "centrifugal water pump". The whole system is linked to a single-phase grid. The PV generator consists of a 30 series photovoltaic modules SM55. The elimination of storage unit reduces the system sizing complexity and economics of the grid connected PV system.

Our control strategy is featured by its multi-loops nature. First, a current loop is designed so that the coupling between the power supply net and the AC/DC rectifier operates with a unitary power factor. Then, a second loop is designed to regulate the output voltage of the AC/DC rectifier to an optimal reference value. The voltage reference optimality is to be understood in the sense that a maximum power must be extracted from the photovoltaic

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generator regardless of solar radiation, This optimal voltage will be determined online using an MPPT method that was developed by A. EL Fadili et al. (2013b,c); EL Fadili *et al.* (2014) and that proved to be a faster searching technique of maximum power point for the PV array, (compared to existing techniques, e.g. RCC, IncCond and P&O). Furthermore, the new method offers, an MPPT without oscillates about the maximum power point and without using the power, current and voltage derivatives, avoiding thus divide-by-zero singularity problems. Finally, a bi-variable loop is designed to make the water flow rate track its varying reference value and regulate the rotor flux norm to its nominal value.

The paper is organized as follows: in Section 2, the system modelling is presented; Section 3 is devoted to the controller design; the controller tracking performances are illustrated through numerical simulations in Section 4. A conclusion and a reference list end the paper.

2. SYSTEM MODELLING

The controlled system is illustrated by Fig. 1. It includes a combination of AC/ DC rectifier connected to PV generator (PVG), on one hand, and a on the other hand, the “DC/AC inverter - squierel cage induction motor”operates a “centrifugal water pump”. The whole is linked to the single-phase grid. The rectifier is a AC/DC converter operating, like the inverter, according to the known Pulse Width Modulation (PWM) principle. The PV generator consists of a 30 series photovoltaic modules SM55.

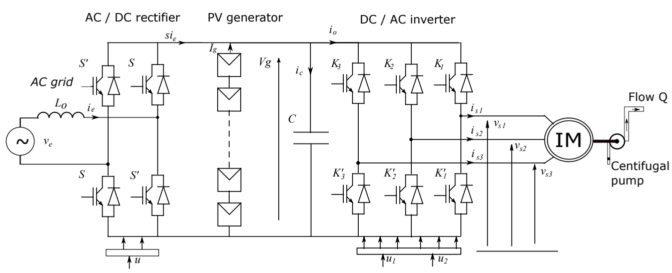

Figure 1. General diagram of the controlled system.

2.1 Photovoltaic generator model

The direct conversion of the solar energy into electrical power is obtained by solar cells. The traditional (I_p-V_p) ideal characteristics (i.e. $R_s = 0$, $R_{sh} = \infty$) of a solar array are given by the following equation (Tan *et al.*, 2004):

$$I_p = I_{ph} - I_o \left\{ exp(AV_p) - 1 \right\} \tag{1}$$

where

$$A = \frac{q}{\gamma KT}, \qquad I_{ph} = \left[I_{SCR} + K_I(T - T_r) \right] \frac{\lambda}{1000}$$

$$I_o = I_{or} \left[\frac{T}{Tr} \right]^3 exp \left[\frac{qE_{GO}}{\gamma K} \left(\frac{1}{Tr} - \frac{1}{T} \right) \right]$$

Where I_{ph} is the photocurrent (generated current under a given radiation); I_o is the cell reverse saturation current; I_{or} is the cell saturation current at T_r; I_{SCR} is the short circuit current at $298.15K$ and $1kW/m^2$; K_I is the short circuit current temperature coefficient at I_{SCR}; λ is the solar radiation; E_{GO} is the band gap for silicon; γ is the ideality factor; T_r is the reference temperature; T is the cell temperature; K is the Boltzman's constant and q is the electron charge. The analytical expressions of I_{ph} and I_o can be found in many places, see e.g. Tan *et al.* (2004). Here, let us just note that these only depend on the temperature T and radiation λ. The PVG is composed of many strings of PV modules in series, connected in parallel, in order to provide the desired values of output voltage and current. This PVG exhibits a non linear (I_g-V_g) characteristics given, approximately and ideally, by the following equation:

$$I_g = I_{phg} - I_o \left\{ exp(A_g V_g) - 1 \right\} \tag{2}$$

where V_g is the PVG voltage, I_g is the PVG current, $A_g = A/N_s$ is the PVG constant, $I_{phg} = N_p I_{ph}$ is the photocurrent of the PVG, $I_{og} = N_p I_o$ is the saturation current of the PVG, N_s is the number of PV connected in series and N_p is the number of parallel paths.

A PV array module considered in this paper is the $SM55$. It has 36 series connected mono-crystalline cells.

2.2 Modeling ‘AC/DC rectifier’

The power supply net is connected to a H-bridge converter which consisting of four IGBT's with anti-parallel diodes for bidirectional power flow mode (see Fig. 1). Applying Kirchhoff's laws, this subsystem is described by the following set of differential equations:

$$\frac{di_e}{dt} = \frac{v_e}{L_o} - \frac{sV_g}{L_o} \tag{3}$$

$$\frac{dV_g}{dt} = \frac{si_e}{2C} + \frac{I_g}{2C} - \frac{i_o}{2C} \tag{4}$$

where i_e is the current in inductor L_o, V_g denotes the voltage in capacitor $2C$ (output of PV), I_g designates the PV output current, $v_e = \sqrt{2}E\cos(\omega_e t)$ is the sinusoidal net voltage (with known constants E, ω_e), i_o designates the input current inverter, and s is the switch position function taking values in the discrete set {-1,1}. Specifically:

$$s = \begin{cases} 1 \ if \ S \ \ On \ \ and \ S' \ Off \\ -1 \ if \ S \ Off \ and \ S' \ \ On \end{cases} \tag{5}$$

The above (instantaneous) model describes accurately the physical rectifier. Then, it is based upon to build up converter simulators. However, it is not suitable for control design due to the switched nature of the control input s. As a matter of fact, most existing nonlinear control approaches apply to systems with continuous control inputs. Therefore, control design for the above converter will be performed using the following average version of (3-4) (Ortega et al. (1996)):

$$\frac{dx_1}{dt} = \frac{v_e}{L_o} - \frac{ux_2}{L_o} \tag{6}$$

$$\frac{dx_2}{dt} = \frac{ux_1}{2C} + \frac{I_g}{2C} - \frac{i_o}{2C} \tag{7}$$

where, $x_1 = \bar{i}_e$, $x_2 = \overline{V}_g$, $u = \bar{s}$, are the average values over cutting periods of i_e, V_g and s, respectively.