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Small-signal modelling and control of photovoltaic based water pumping system

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ABSTRACT

This paper studies small-signal modelling and control design for a photovoltaic (PV) based water pumping system without energy storage. First, the small-signal model is obtained and then, using this model, two proportional–integral (PI) controllers, where one controller is used to control the dc-link voltage and the other one to control the speed of induction motor, are designed to meet control goals such as settling time and peak overshoot of the closed loop responses. The loop robustness of the design is also studied. For a given set of system parameters, simulations are carried out to validate the modelling and the control design.

1. Introduction

Lack of electricity is one of the main hurdles in the development of rural areas of many countries. Moreover, the environmental issues such as pollution and global warming effects are driving researchers towards the development of renewable energy sources including solar system. One of the most important applications of photovoltaic (PV) based stand alone system is for water pumping, particularly in regions that have a considerable amount of solar radiation, but no access to national grids.

In [1–3], authors proposed PV based water pumping system in which dc motor was used to drive the pump. However, among the various motors, the use of induction motor (IM) for pumping application is an attractive proposal because of the absence of commutator and brushes, which provides reliable, economical, and maintenance-free operations [4–7]. In [6], authors proposed a water pumping system with battery storage and dc–dc converter for maximum power point tracker (MPPT). Although battery provides flexibility in the operation and surplus power from PV can be stored, it increases the overall cost of the system (depending upon rating and type of batteries) [8]. Moreover, remote water pumps are often designed to run without battery backup, since water pumped out of the ground during daylight hours can be stored in a holding tank for use any time [9,10]. The flexible operation of PV based water pumping system without battery storage was presented in [11]. To the best of authors' knowledge, however, the small-signal modelling of the PV based water pumping system and control design using the same are not discussed in the literature. This is essentially required for better analysis and ease design of the system. It may be noted in this context that some works were carried out on small-signal modelling and analysis of wind based power generation systems in [12,13]. However, the same for PV based systems is not attempted in literature so far.

This paper considers the PV based pumping system without battery and dc–dc converter (for MPPT), as noted in [11]. The first aim of this paper is to obtain a small-signal model of the system. Using this small-signal model, next, the design of the PI controllers employed in the system is carried out to meet control objectives such as settling time and peak overshoot of the responses. The model and the control design are numerically validated for a given set of system parameters.

2. The PV based water pumping system

The PV based water pumping system considered in this paper is shown in Fig. 1 [11]. The detailed control scheme (which is also available in [11]) is shown in Fig. 2. The system consists of the following subsystems.

2.1. The PV system

The equivalent circuit of the PV module considered is shown in Fig. 3(a), where I_{PV}, V_{PV} are the PV module current and voltage,

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respectively, I_{ph} is the PV module photocurrent, and R_{sh} and R_s are intrinsic shunt and series resistances of the module, respectively. Note, R_{sh} is very large and R_s is very small. The current of the module is given by [14,15]

$$I_{PV} = I_{ph} - I_d - I_{sh} \quad (1)$$

$$I_{ph} = G\frac{I_{sc}}{G^*} \quad (2)$$

where I_{sc} is the short circuit current of the module, G is the solar irradiance (W/m^2), G^* is the nominal irradiance, and

$$I_d = I_0\left(e^{V_D/V_t} - 1\right) \quad (3)$$

where $V_D = V_{PV} + I_{PV}R_s$, $V_t = \overline{A}K_1Tn_s/q$, $q = 1.602 \times 10^{-19}$ C is the electron charge, $K_1 = 1.3806 \times 10^{-23}$ J/K is Boltzman's constant, $\overline{A}$ is the p–n junction's ideality factor (=1.02, considered in this paper), T is the array temperature (in K), n_s is the number of solar cells in the module, I_0 is the diode reverse saturation current, and

$$I_{sh} = \frac{V_D}{R_{sh}} \quad (4)$$

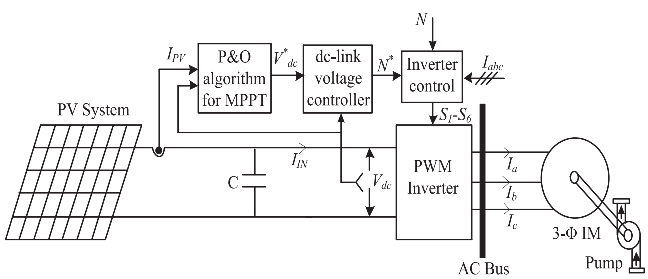

Fig. 1. The PV based water pumping system.

The parameters of the PV module considered are presented in Section 5 and Table 2. The power–voltage characteristic of the module for different irradiances is shown in Fig. 3(b).

2.2. The MPPT

For best utilization, the PV module must be operated at their maximum power point. To achieve this, according to the perturb and observe (P&O) algorithm [15,16], the MPPT adjusts the terminal voltage of PV module to V_{mpp}, whose value at an instant k, say, is related to the corresponding value at the previous instant by [11]

$$V_{mpp}(k) = V_{mpp}(k-1) + M\ \text{sign}\left(\frac{dP_{PV}}{dV_{PV}}\right) \quad (5)$$

with $V_{mpp} = 0$, $P_{PV} = V_{PV}I_{PV}$, and M being the step size (=0.01, considered in this paper). As shown in Fig. 1, since the PV module is directly connected to the dc bus, the dc-link voltage (V_{dc}) equals to the output voltage of PV (V_{PV}). Therefore, the voltage, V_{mpp}, generated by P&O algorithm is, henceforth, treated as the reference dc-link voltage V^*_{dc}.

2.3. DC-link voltage controller

The aim of using dc-link voltage controller in Fig. 1 is to set the reference speed (N^*) of the induction motor so that dc-link voltage (V_{dc}) tracks the voltage output of the MPPT (V^*_{dc}). The components of this controller are shown in Fig. 2, where PI_{dc} is the PI controller for dc-link voltage control, P is the number of poles of the motor. Notice that a saturation block is used to limit the reference speed [11].

2.4. PWM inverter and its controller

The PWM inverter is used to control the speed of the motor. The inverter controller employed for this purpose is based on

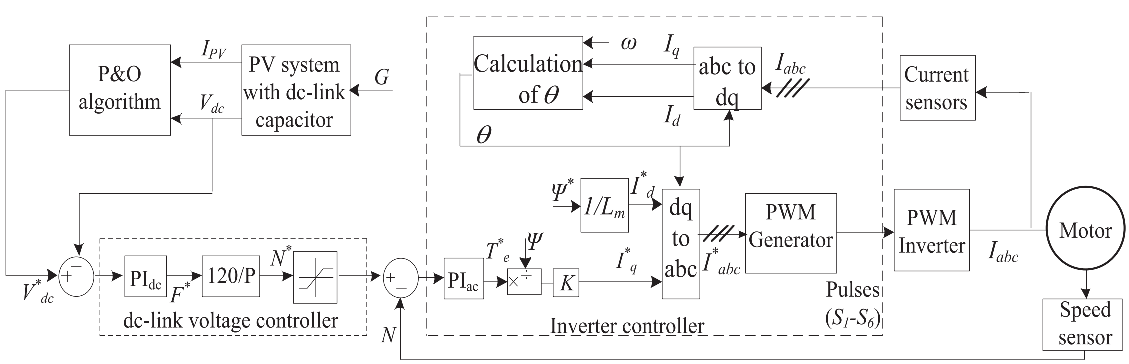

Fig. 2. The whole system with component details.

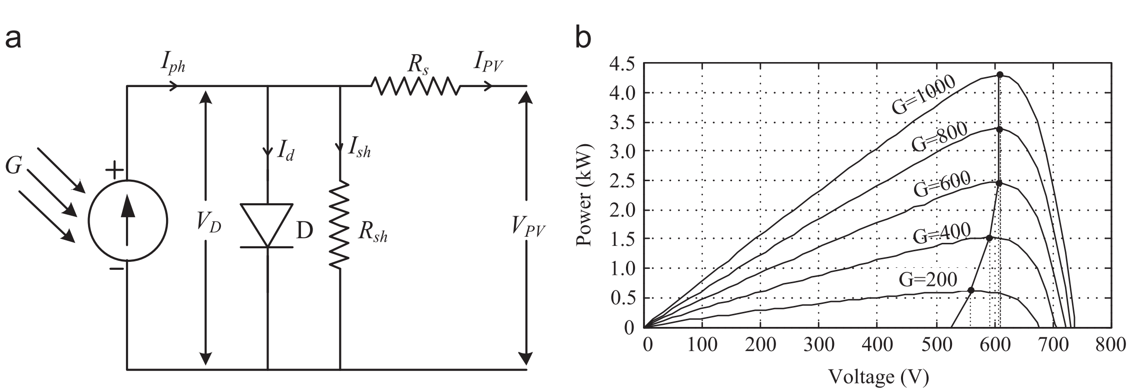

Fig. 3. (a) PV module equivalent circuit and (b) PV curves at different irradiances.