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Improved adaptive input voltage control of a solar array interfacing current mode controlled boost power stage

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ABSTRACT

Nonlinear characteristics of photovoltaic generators were recently shown to significantly influence the dynamics of interfacing power stages. Moreover, since the dynamic resistance of photovoltaic generators is both operating point and environmental variables dependent, the combined dynamics exhibits these dependencies as well, burdening control challenge. Typically, linear time invariant input voltage loop controllers (e.g. Proportional-Integrative-Derivative) are utilized in photovoltaic applications, designed according to nominal operating conditions. Nevertheless, since actual dynamics is seldom nominal, closed loop performance of such systems varies as well. In this paper, adaptive control method is proposed, allowing to estimate photovoltaic generator resistance online and utilize it to modify the controller parameters such that closed loop performance remains nominal throughout the whole operation range. Unlike previously proposed method, utilizing double-grid-frequency component for estimation purposes and suffering from various drawbacks such as operation point dependence and applicability to single-phase grid connected systems only, the proposed method is based on harmonic current injection and is independent on operating point and system topology.

1. Introduction

The demand for more reliable power electronics systems has been constantly increasing during recent decade [1]. Moreover, renewable energy based electricity generation demonstrate tremendous amount of progress [2]. These trends call for more robust and high-performance photovoltaic generation units [3]. Until recently, renewable energy sources based systems were traditionally designed to extract as much energy as possible utilizing different maximum power point tracking (MPPT) algorithms [4]. Recent development of microgrids formulated additional requirements on renewable energy sources operational strategy [5]. These systems are now required to operate below MPP as well in order to match generation and consumption in isolated systems [6]. Thus, additional control challenges are now being posed as well [7].

It is well known that solar arrays (SA) output is highly dependent on environmental variables [8]. Recently, SA dynamic resistance was shown to be strongly correlated with operating point as well [9]. Consequently, combined SA-interfacing converter system dynamics become operating point and environmental variables dependent as well [10]. This implies varying closed-loop behavior when governed by typical linear time invariant loop compensator [11]. In order to cope with time-varying nature of photovoltaic generators, robust and/or adaptive control approaches are obviously required to attain predetermined closed-loop performance throughout the whole operation range [12]. Nevertheless, until today, the only attempt to apply adaptive control approach to control SA terminal voltage was presented in [13], where input voltage of a SA-fed current-controlled boost power stage (which is probably most frequently utilized as photovoltaic generator interfacing converter [14]) was regulated, utilizing adaptive control method based on real-time SA dynamic resistance estimation. While yielding satisfactory results, the presented approach suffers from several drawbacks, namely operation point dependence, applicability to single-phase AC systems only and noise immunity, as revealed in this paper. Consequently, in order to overcome these disadvantages, an improved adaptive approach is proposed in this paper, utilizing different algorithm to estimate the dynamic

Abbreviations: SA, Solar array; MPPT, Maximum power point tracking; PI, Proportional-Integrative; MPP, Maximum Power Point; BPF, Band Pass Filter; RMS, Root Mean Square; IV, Current–Voltage; PV, Power–Voltage.

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resistance of a photovoltaic module. The proposed method is based on harmonic current injection into inner control loop of the interfacing converter control structure and allows attaining robust closed loop performance throughout the whole operating range. The proposed method is validated by applying to single and three phase grid connected photovoltaic systems.

The rest of the paper is organized as follows. Problem formulation is given in Section 2. The solution proposed in [13] is explained in Section 3, followed by revealing its inherent drawbacks in Section 4. The proposed improved solution is described in Section 5. Validation results are given in Section 5 and the paper is concluded in Section 6.

2. Problem formulation

The system under consideration is shown in Fig. 1, where capacitor (C_{in}) – terminated SA is interfaced by a DC–DC boost converter, feeding bulk capacitance C_b, which in turn is loaded by a single-phase grid-connected inverter, operating with unity power factor.

Typical control arrangement of a grid-connected photovoltaic system operating in MPPT mode is shown in Fig. 2 [10]. Each converter employs cascaded, dual-loop control arrangement aimed to regulate its input voltage, i.e. each voltage controller generates reference command to corresponding inner current loop controller, which in turn calculates the converter duty cycle d. The reference value of boost converter input voltage v_{IN}^* is dictated by a maximum power point tracking (MPPT) algorithm while the reference value of inverter input voltage v_B^* is usually set to a constant value (e.g. 400 V or 800 V for single/three phase systems, respectively).

Power-level average equivalent circuit of the system is shown in Fig. 3. At boost converter input, SA operates as voltage controlled power source p_{SA} while the inductor of the current mode controlled converter is represented by a current source i_L. At the output side, bulk capacitance "sees" a power source p_{PV}, representing SA power processed by the boost converter and a power load p_G, drawn by the grid interfaced inverter under current mode control.

Equivalent circuit of the SA, derived from physical principles, is shown in Fig. 4 [8]. It consists of a photocurrent source I_{PV}, recombination current I_D, equivalent shunt capacitance C_{PV} and equivalent shunt and series resistances R_{SH} and R_S, respectively. For mono- and poly-crystalline silicon equivalent shunt and series resistances may be considered irradiation and temperature independent. Equivalent capacitance of a SA depends on operation point as well as on environmental conditions; nevertheless, it can be neglected since in addition to obtaining relatively small values, it is usually offset by the input capacitance of the boost power stage C_{in}.

Recombination losses are usually modeled by one or more semiconductor diodes connected in parallel, drawing current given by general form of

$$I_D = \sum_k I_{0k}\left(e^{\frac{v_{PV}}{\alpha_k V_T}} - 1\right), \tag{1}$$

where I_{0k} and α_k are reverse saturation current and ideality factor of kth diode, respectively, and V_T is thermal voltage. Therefore, denoting

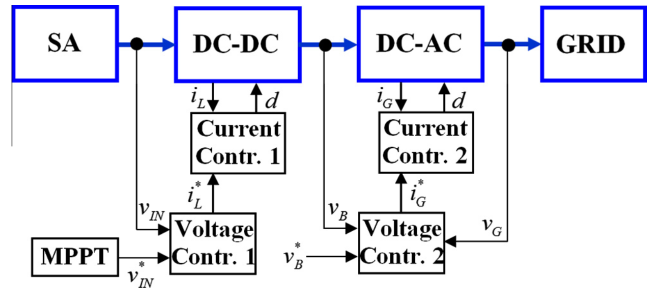

Fig. 2. Typical control structure of grid-connected photovoltaic system.

$$R_D^{-1} = \left(\frac{dI_D}{dv_{PV}}\right)^{-1} = \sum_k \frac{I_{0k}}{\alpha_k V_T} e^{\frac{v_{PV}}{\alpha_k V_T}}, \tag{2}$$

SA dynamic resistance is given by

$$R_{PV} = -\left(\frac{di}{dv}\right)^{-1} = R_S + R_{SH}||R_D = R_{PV}(G, T, v), \tag{3}$$

obviously depending on irradiation G, temperature T and electrical operating point. Parameter values of SA equivalent circuit may be obtained utilizing one of well-established approaches. For example, amorphous and exotic SA parameters may be extracted using the approach presented in [15]. Silicon SA parameters extraction methods under typical illumination are given in [16]. In case of highly illuminated cells, the approach proposed in [17] may be utilized.

Combined switching-cycle-averaged DC side behavior of the system is governed by the following system of equations,

$$\begin{aligned} C_{in}\dot{v}_{IN}(t) &= I_{SA} - R_{PV}^{-1} v_{IN}(t) - i_L(t) \\ L\dot{i}_L(t) &= v_{IN}(t) - (1 - d(t))v_B(t) \\ C_b\dot{v}_B(t) &= (1 - d(t))i_L(t) - \frac{p_G(t)}{v_B(t)}, \end{aligned} \tag{4}$$

where $I_{SA} = I_{PV} \cdot R_{SH}||R_D \cdot (R_{SH}||R_D + R_S)^{-1}$ is the Norton equivalent current of the SA and d is boost converter duty cycle. Splitting time-varying quantities into AC and DC terms,

$$\begin{aligned} v_{IN}(t) &= \tilde{v}_{IN}(t) + V_{IN} \quad i_L(t) = \tilde{i}_L(t) + I_L \\ v_B(t) &= \tilde{v}_B(t) + V_B \quad d(t) = \tilde{d}(t) + D \end{aligned} \tag{5}$$

and substituting into (4) reveals the subsequent small-signal dynamics,

$$\begin{aligned} C_{in}\dot{\tilde{v}}_{IN}(t) &= -R_{PV}^{-1}\tilde{v}_{IN}(t) - \tilde{i}_L(t) \\ L\dot{\tilde{i}}_L(t) &= \tilde{v}_{IN}(t) - (1 - D)\tilde{v}_B(t) + V_B\tilde{d}(t) \\ C_b\dot{\tilde{v}}_B(t) &= V_B^{-1}(1 - D)I_L\tilde{v}_B(t) + (1 - D)\tilde{i}_L(t) - I_L\tilde{d}(t) - V_B^{-1}\tilde{p}_G(t), \end{aligned} \tag{6}$$

linearized around an operating point given by

$$\begin{aligned} I_{SA} - R_{PV}^{-1}V_{IN} &= I_L \\ V_{IN} &= (1 - D)V_B \\ (1 - D)I_L &= R_B^{-1}P_G. \end{aligned} \tag{7}$$

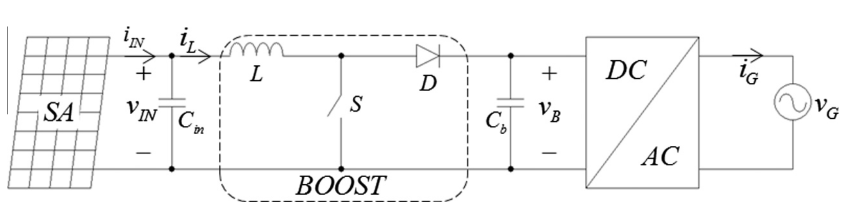

Fig. 1. Typical grid-connected photovoltaic system.