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Voltage Stability of Power Grids with PV Plants using Robust LPV-Control

Moritz Theißen * **Konstantin Schaab** * **Olaf Stursberg** *

* *Control and System Theory, EECS, University of Kassel (Germany). Email: {moritz.theissen, k.schaab, stursberg}@uni-kassel.de*

Abstract: This paper proposes a new approach to control PV plants using linear parameter varying systems (LPVS) to overcome limitations of controllers designed based on single linearizations. The nonlinear PV plant is transformed into an LPVS and a feedback LPV controller is obtained, which is robust against bounded variations in the input matrix. Finally, the LPV controller is compared with a reference controller, and it is shown for an example that the proposed controller outperforms the reference controller by achieving voltage stability.

Keywords: LPV systems, photovoltaic power plant, energy systems, voltage stability, transient stability

1. INTRODUCTION

As the share of grid-connected photovoltaic (PV) power plants becomes increasingly substantial (Braun et al., 2009), their impact on power system stability has to be considered. While the impact of small-scale grid-connected PV power generators with a peak capacity of some kilowatts is relatively small, large-scale PV power plants with a peak capacity of some megawatts have a significant relevance for grid stability (Yazdani and Dash, 2009).

First investigations in the field of large-scale grid-connected PV power plant control have dealt with control strategies for energy supply according to the maximum power point. Another objective was reactive power reduction (with the aim of a power factor close to one), as well as reducing the impact of PV plants on power grids (Yazdani and Iravani, 2006; Yazdani and Dash, 2009). Recent work has taken power grid supply into account, like regulating the AC voltage using existing PV plant controllers with reactive power supply (Cagnano et al., 2011; Yazdani et al., 2011). Developing control strategies to increase the damping of power oscillation was also considered (Shah et al., 2013), as well as the combination of voltage regulation with power storage devices (Taheri et al., 2013).

A fundamental shortcoming of these concepts is that the control designs are based on a single or a few linearizations of a highly nonlinear PV plant system. Thus, this paper proposes a new local control strategy for large-scale grid-connected PV plants using so-called linear parameter varying systems (LPVS). Such models formulate ranges of parameterized matrices to encode the nonlinear dynamics exactly, but with the structure of linear/affine models. A wide range of robust control strategies for LPVS exists. This paper extend the feedback LPV controller, proposed in (Schaab and Stursberg, 2015a,b), to the aim of voltage stability at the point of common coupling (PCC) in the sense of (Kundur et al., 2004).

The remainder of this paper is structured as follows: Section 2 reviews the nonlinear PV plant system connected to a power grid. In Section 3, the nonlinear PV plant system is transformed into a LPVS. The focus of Section 4 is on the synthesis of LPV controllers. Section 5 contains the simulation results, as well as a comparison of the control performances obtained for the LPV controller and a reference controller. Section 6 concludes the paper.

2. NONLINEAR MODEL OF PV PLANT

To illustrate the typical structure of power systems including a PV plant and a small power grid, Fig. 1 shows an example taken from (Yazdani and Dash, 2009). The power grid consists of two transmission lines connecting the three buses PCC, Ld and IB in a row. At bus Ld, a dynamic load is installed. Bus IB is the so-called infinite bus, represented by the voltage source v_{IB} which supplies the power grid. This small power system is an instance of *single machine infinite bus systems* (SMIB), as used in (Schaab and Stursberg, 2015b).

2.1 Power Grid and Dynamic Load Model

In classic transient analysis of power systems, the power grid is simplified to algebraic equations of voltage/power or voltage/current for each grid bus (Kundur et al., 1994; Schaab and Stursberg, 2015b). This appears to be reasonable under the assumption, that the essential time constants of conventional power plants (like synchronous generators) and the power grid are different by order of magnitude (Kundur et al., 1994). In contrast, time constants of PV plants and the power grid are quite similar. Thus, the assumption above appears to fail, if PV plants are contained in the power system. Therefore, the power grid from Fig. 1 is modeled by the differential equations of the currents through the line inductances $L_{\{1,2\}}$ and the voltage at the bus capacity C_l. The capacity C at the bus PCC is part of the PV plant inverter LC-output filter. The power grid differential equations can be obtained by using Kirchhoff's law and is set up in dq-coordinates (Yazdani and Dash, 2009):

$$\dot{i}_{1,d} = -\frac{R_1}{L_1} i_{1,d} + \omega i_{1,q} + \frac{N}{L_1} v_{pcc,d} - \frac{1}{L_1} v_{l,d} \ , \qquad (1)$$

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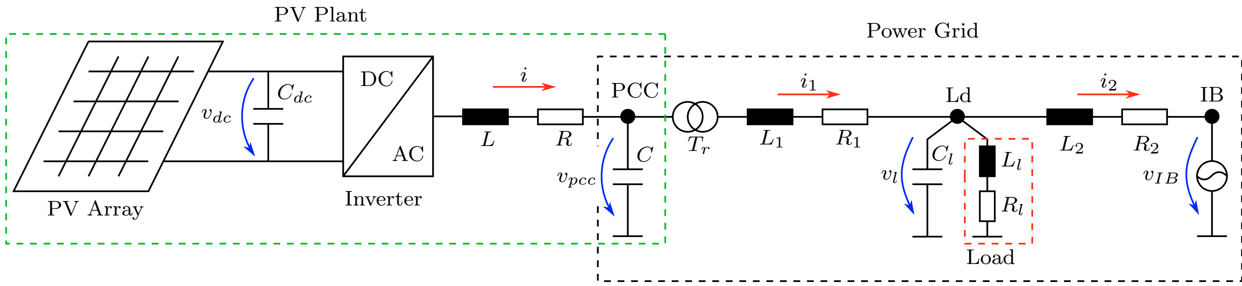

Fig. 1. Three-phase PV plant coupled to a power grid through a transformer, shown as single-line schematic diagram.

$$\dot{i}_{1,q} = -\frac{R_1}{L_1} i_{1,q} - \omega i_{1,d} + \frac{N}{L_1} v_{pcc,q} - \frac{1}{L_1} v_{l,q} \quad , \tag{2}$$

$$\dot{i}_{2,d} = -\frac{R_2}{L_2} i_{2,d} + \omega i_{2,q} + \frac{1}{L_2} v_{l,d} - \frac{1}{L_2} v_{IB,d} \quad , \tag{3}$$

$$\dot{i}_{2,q} = -\frac{R_2}{L_2} i_{2,q} - \omega i_{2,d} + \frac{1}{L_2} v_{l,q} - \frac{1}{L_2} v_{IB,q} \quad , \tag{4}$$

$$\dot{v}_{l,d} = \omega v_{l,q} + \frac{1}{C_l} i_{1,d} - \frac{1}{C_l} i_{2,d} - \frac{1}{C_l} i_{l,d} \quad , \tag{5}$$

$$\dot{v}_{l,q} = -\omega v_{l,d} + \frac{1}{C_l} i_{1,q} - \frac{1}{C_l} i_{2,q} - \frac{1}{C_l} i_{l,q} \quad . \tag{6}$$

The d- and q-components of the line currents are denoted by $i_{1,\{d,q\}}$ and $i_{2,\{d,q\}}$. Likewise, $v_{l,\{d,q\}}$ are the dq-voltages at bus Ld, $v_{pcc,\{d,q\}}$ at bus PCC and $v_{IB,\{d,q\}}$ at the infinite bus IB. The transformer T_r steps the nominal PV plant voltage (480V) up to the nominal power grid voltage (6.6kV). For the sake of simplicity the transformer is reduced to the voltage ratio $N = 6.6\text{kV}/480\text{V} = 13.75$, as well as its leakage inductance and resistance, which are included in the line inductance L_1, and the resistance R_1. Thus, the ratio N in (1) and (2) implies the different voltage levels in $v_{pcc,\{d,q\}}$ and $v_{l,\{d,q\}}$. The grid frequency is assumed to be constant with $\omega = 2\pi 60\text{s}^{-1}$.

The dynamic load is modeled as a resistive-inductive load (R_l and L_l) at bus Ld. This leads to the following description of the load currents $i_{l,\{d,q\}}$:

$$\dot{i}_{l,d} = -\frac{R_l}{L_l} i_{l,d} + \omega i_{l,q} + \frac{1}{L_l} v_{l,d} \quad , \tag{7}$$

$$\dot{i}_{l,q} = -\frac{R_l}{L_l} i_{l,q} - \omega i_{l,d} + \frac{1}{L_l} v_{l,q} \quad . \tag{8}$$

2.2 PV Plant

The DC interface of the PV plant consists of a PV array with 176 PV strings in parallel, and 1500 PV cells per string in series (Yazdani and Dash, 2009). The nonlinear characteristic curve regarding the voltage-current for the overall PV array is:

$$i_{pv}(S, \vartheta, v_{dc}) = I_{ph}(\vartheta) S - I_s \left(e^{\beta_{pv}(\vartheta) v_{dc}} - 1 \right) \quad . \tag{9}$$

The total short-circuit current of all photovoltaic strings in parallel $I_{ph}(\vartheta)$ depends on the p-n junction temperature ϑ, which is assumed to be constant at $\vartheta = 300\text{K}$. Furthermore, $I_{ph}(\vartheta)$ gets weighted with the normalized solar irradiation S, where $S = 1$ references to the solar irradiation $1000\text{W}/\text{m}^2$. The reverse saturation current I_s is caused by the p-n junction, and is aggregated for all strings in parallel. The photovoltaic cell coefficient, which describes the form of the nonlinear PV characteristic, is denoted by $\beta_{pv}(\vartheta)$.

The DC interface dynamics can be represented by the balance of the power generated by the PV array p_{pv} and the AC real power output of the inverter p_{dc} (by neglecting the inverter losses). This is shown in (10), using the squared DC voltage v_{dc} as state variable $\nu_{dc} = v_{dc}^2$ (Yazdani and Dash, 2009):

$$\dot{\nu}_{dc} = \frac{2}{C_{dc}} \underbrace{i_{pv} v_{dc}}_{p_{pv}} - \frac{2}{C_{dc}} \underbrace{\frac{3}{2} (i_d e_d + i_q e_q)}_{p_{dc}} \quad . \tag{10}$$

The inverter AC side currents are $i_{\{d,q\}}$, while $e_{\{d,q\}}$ are the inverter AC output voltages:

$$e_d = K_d \frac{v_{dc}}{2} \quad , \qquad e_q = K_q \frac{v_{dc}}{2} \quad . \tag{11}$$

The control inputs $K_{\{d,q\}}$ can be converted into the duty cycles for the power electronic switches in the inverter.

The AC interface comprises the inverter LC-output filter. Likewise, the differential equations for the filter-inductance and the filter-capacity can be deduced from Kirchhoff's law:

$$\dot{i}_d = -\frac{R}{L} i_d + \omega i_q + \frac{1}{L} \left(K_d \frac{v_{dc}}{2} - v_{pcc,d} \right) \quad , \tag{12}$$

$$\dot{i}_q = -\frac{R}{L} i_q - \omega i_d + \frac{1}{L} \left(K_q \frac{v_{dc}}{2} - v_{pcc,q} \right) \quad , \tag{13}$$

$$\dot{v}_{pcc,d} = \omega v_{pcc,q} + \frac{1}{C} i_d - \frac{N}{C} i_{1,d} \quad , \tag{14}$$

$$\dot{v}_{pcc,q} = -\omega v_{pcc,d} + \frac{1}{C} i_q - \frac{N}{C} i_{1,q} \quad . \tag{15}$$

2.3 dq-Reference Signals

In classic transient analysis of power systems, the voltage at a grid node with index h is normally given as the voltage amplitude v_h and the voltage angle Θ_h. These quantities are formulated in dq-representation by:

$$v_{h,d} = v_h \cos(\Theta_h - \Theta_{dq}) \quad , \tag{16}$$

$$v_{h,q} = v_h \sin(\Theta_h - \Theta_{dq}) \quad , \tag{17}$$

where Θ_{dq} is the dq-reference angle (Yazdani and Dash, 2009). The power grid in Fig. 1 consists of the three grid nodes $h \in \{PCC, Ld, IB\}$.

As it is justified to model the infinite bus voltages $v_{IB,\{d,q\}}$ as being constant, it is obvious to select the infinite bus voltage angle Θ_{IB} as the dq-reference angle: $\Theta_{dq} = \Theta_{IB}$. Therefore, the infinite bus can be seen as a sub-station which connects this small power grid to an infinitely strong, but far away power system. Hence, the voltages of the infinite bus simplify to:

$$v_{IB,d} = v_s \qquad v_{IB,q} = 0 \quad . \tag{18}$$

For the sake of simplicity, Θ_{IB} and therefore Θ_{dq} are assumed to be zero. This is suitable and justified, since