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A generic model of two-stage grid-connected PV systems with primary frequency response and inertia emulation

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ABSTRACT

Photovoltaic (PV) stations are increasingly becoming subject to grid code requirements that include frequency response and active power control capability. The main goal of this paper is to propose a generic model for a two-stage grid-connected PV system with frequency response capability, suitable for power system studies. The proposed model includes a suitable control scheme, which provides both droop and inertial response, as well as the ability to operate at a scheduled active power reserve, enabling thus the provision of under-frequency response. A linearized small-signal model is developed to assess the stability of the proposed PV power control loop when the PV generator provides frequency response, whereas time-domain simulations are performed in order to quantify the benefits achieved by droop-type and inertia frequency controllers, including a discussion on the selection of their parameters. The analysis demonstrates the satisfactory performance of the proposed PV system model, which provides all functionality required by grid codes in the context of active power control.

1. Introduction

Present day grid codes impose technical requirements to distributed generation (DG) stations, including photovoltaic (PV) plants. Among these, particularly important is the provision of frequency response, as well as the ability to implement power curtailment commands issued by the network operator [1–3]. It is imperative that DG models used in power system studies dealing with future networks with high levels of DG penetration provide the required functionality in the context of grid code compatibility.

DG contribution to frequency control is a well-known issue in the literature. For instance, droop and inertia control schemes are examined in [4–8] for wind turbines (WTs), whereas similar approaches can be found in [9–11] for energy storage systems (ESS) and in [12–16] for PV stations equipped with internal ESS.

In the case of PV stations without internal ESS, DC link capacitors are usually characterized by high charging rates (in the range of milliseconds) and therefore the challenge of frequency response is transposed to the PV generator and its control. Literature on active power control of PV plants without internal ESS is still limited, concerning both its technical implementation and the expected benefits [17]. For single-stage PV systems, bespoke power control strategies are proposed in [18,19], in order to minimize frequency variations in a small power system, employing a fuzzy logic controller and a minimal order observer, respectively. In [20–22], particular attention is placed on the provision of droop-type response, while in [21] an emergency controller is also proposed in order to curtail power after severe over-frequency events.

Regarding two-stage PV systems, the provision of frequency response becomes a more challenging task from a control perspective, as the DC link voltage of the PV inverter is decoupled from the PV generator voltage, thus providing enhanced flexibility in operation and control of such systems [23–26]. However, relevant references on the subject are again limited to droop-type control [27,28], while authors in [29] propose a method to regulate the operating point of the PV generator below the maximum power point (MPP), by controlling the PV array voltage to a specific fraction of its open circuit voltage. However, it is not addressed how this fraction can be determined in relation to the desired level of power reserve which might be imposed by the network operator. Further, a different control method is proposed in [30], which is based on proportional-integral (PI) control of the grid frequency, without however addressing how the controller settings can be adjusted to provide the desired droop or inertial response, or how to follow external active power commands (e.g. reserve levels), as stipulated by grid codes.

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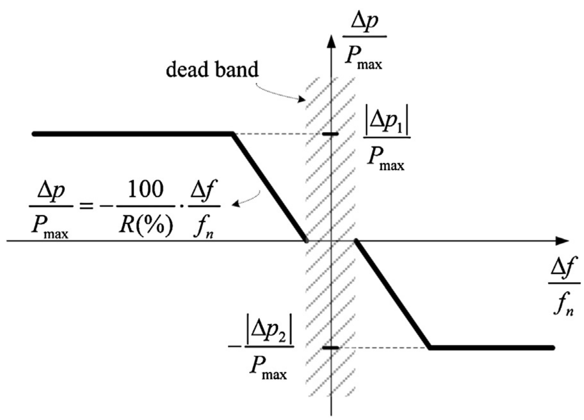

Fig. 1. Active power regulation in FSM [1].

A sufficiently detailed PV system model, providing all required functionality in terms of active power control and frequency control, is still missing from the literature. In this paper, such a model is introduced for a two-stage grid-connected PV system without ESS, which is suitable for power system studies. The required frequency response is achieved by regulation of the PV generator output power via the DC/DC converter. The proposed control scheme permits the following alternative operating modes: (a) conventional maximum power point tracking (MPPT), (b) droop and (c) inertial frequency response, (d) operation at a given power reserve, which in turn enables under-frequency response. The frequency controller is integrated in the DC/DC converter controller of [31], which permits regulation of the generated PV power to a given reference.

To evaluate the dynamic response of the proposed PV system model, a small isolated network is used as a study-case system, comprising a diesel unit (DU), a full-power converter wind turbine (FCWT), a PV plant and local load. The disturbances considered include load changes as well as stochastic variations of the wind speed of the connected WT.

The paper is organized as follows: The main frequency response requirements stipulated by grid codes are briefly discussed in Section 2. The modeling approach adopted for each generating unit is presented in Section 3. The proposed control schemes for the DC/DC converter and PV inverter are outlined in Section 4. Time-domain simulations are presented in Section 5 and the main conclusions are summarized in Section 6. Parameter values are provided in Appendix.

2. Frequency response requirements

Fig. 1 depicts a typical frequency response characteristic, from the new ENTSO-E Code for Generators [1]. The objective of this requirement is for each generating unit to automatically adjust active power output in case of frequency deviations. According to Fig. 1, two operating modes are identified:

- "Frequency sensitive mode-over-frequency (FSM-O)": the generating unit is expected to curtail active power proportionally (droop-type control) to the frequency increase $\frac{\Delta f}{f_n}$, where f_n is the nominal system frequency. This operating mode is limited by the minimum regulating level $-\frac{|\Delta p_2|}{P_{\max}}$ that the station is allowed to operate, where $P_{\max}$ is the maximum capacity.
- "Frequency sensitive mode-under-frequency (FSM-U)": If under-frequency events occur, the generating unit is expected to release additional active power up to its maximum capacity $P_{\max}$. The resulted under-frequency response depends on the operating and ambient conditions of the station. The active power range $\frac{|\Delta p_1|}{P_{\max}}$ in Fig. 1 varies from 1.5 to 10% [1].

The frequency dead-band depicted in Fig. 1 lies in the range of 0–500 mHz, whereas the droop constant R varies from 2 to 12% [1]. Both parameters are provided by the network operator. Generating units are also required to receive external active power set-points by the network operator via a suitable control interface and adjust their power output within specified time intervals and error tolerances. A similar requirement is also foreseen in the German feed-in tariff law for PV stations [3], which must be able to limit their active power output down to 70% of the installed PV capacity.

Apart from the conventional droop-type control, the ENSTO-E Network Code foresees also the ability of a generating unit to provide synthetic inertial response in order to limit the rate of change of frequency (ROCOF) following major system disturbances. For power plants without inherent inertial response capability (e.g. inverter-interfaced units), an amendment to the power plant controller is required in order to emulate inertial response [1].

The aforementioned requirements are used as a reference in the rest of this paper, in order to develop a PV system model offering a wide range of alternative active power control modes, in the context of grid code compatibility.

3. System modeling and control

As already mentioned in Section 1, the proposed PV system model will be exploited in the paper to investigate the potential for frequency regulation offered by PV plants without internal ESS. For this purpose, a small isolated network is selected as the study-case system, comprising a DU, a FCWT, a PV plant and local load. In the following, the main modeling guidelines adopted for each generating unit are briefly presented.

The PV generator is modeled by the standard single-diode equivalent circuit [32,33], whose accuracy suffices for the purpose of this study. Its equations along with typical parameter values can be found in [32]. The two-stage power conversion system of the PV plant is depicted in Fig. 2. It comprises two parallel 3-phase DC/AC inverters connected to the MV network through a three-winding transformer [34], along with multiple DC/DC converters connected in parallel at the DC side [25]. In this work, to simplify converter modeling and reduce computational burden, a single PV array and DC/DC converter is assumed for each DC/AC inverter. As it is further explained in Section 4, the DC/DC converter regulates the operating point of the PV array, while the PV inverter controls the DC link voltage to its reference value. Parameter values are given in Table 1 of Appendix.

The simple DU model employed in this study is illustrated in block diagram form in Fig. 3 [35]. The diesel engine and the valve actuator servomechanism are represented by first-order lags, with time constants T_D and T_{SM}, respectively. Inputs to the synchronous generator model are the mechanical power p_D and the terminal voltage v_t, whereas outputs are the generator speed, ω_D, and the electrical output power p_e. Parameters of the speed governor are the droop constant R and the integral (isochronous) control gain K_i, which eliminates the steady-state frequency error. An IEEE Type I automatic voltage regulator and excitation system is assumed and the standard 6th-order dq model available in Matlab/Simulink library is employed for the synchronous generator. Parameter values are given in Table 2 of Appendix.

The typical configuration of a FCWT based on a multi-pole permanent magnet synchronous generator (PMSG) is illustrated in Fig. 4. The PMSG is controlled by the generator side converter which implements the MPPT strategy, whereas the grid side converter