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Modeling the three-phase short-circuit contribution of photovoltaic systems in balanced power systems

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ABSTRACT

A high penetration of Photovoltaic (PV) systems into power networks can alter the fault currents and negatively impacts on the operation of the protection systems. In this paper, a new analytical model of the fault contribution of a three-phase PV system equipped with a voltage source converter is proposed. Such a model extends the classical steady-state short-circuit analysis to balanced active power networks including PV systems, with the aim to analyze their impact on the breaking capacity of the interrupting devices. The proposed model: (i) takes into account environmental conditions and VSC current limits; (ii) includes the effects of reactive power injections by a detailed representation of different type of VSC control systems; and (iii) can be easily integrated in a software package for power system analysis. The proposed approach is validated by comparing analytical results with time-domain simulations of the IEEE benchmark PV system. Furthermore, it is used to evaluate the impact of a large penetration of PV systems on the fault currents.

1. Introduction

Grid-connected photovoltaic (PV) systems contribute to the short-circuit current during a fault, modifying the short-circuit capacity of the power systems [1,2]. Indeed, the short-circuit contribution of a single PV system is negligible because of its small size and the limits on the current flowing through the inverter. However, a high penetration of PV systems into the power networks can alter the fault currents enough to negatively impact on the operation of the protection systems [1,3,4]. Consequently, the contribution of PV systems to the fault current cannot be ignored and must be modeled, so as to extend the traditional short-circuit analysis to power networks with a large penetration of PV systems.

As well-known, the short-circuit analysis of power systems has many objectives; among the most important, it allows to evaluate the magnitudes of the fault currents to rate the breaking capacity of the interrupting devices and it provides a basis for the coordination of the system protections in order to guarantee the selectivity.

The contribution to the short-circuit current depends on several factors: the environmental conditions; the maximum current that can flow through the inverter, due to the low thermal inertia of switching devices; the self-protections of the PV systems; the location and the type of the fault; and the inverter control system, which is the main responsible of the behavior of PV system during faults [5,6].

Presently, the primary function of the inverter control system is to regulate its active power output according to the maximum power extractable from the solar radiation; at the same time, the possibility to perform reactive power regulation has not completely been exploited yet and the PV system often operates at unity power factor in some operating conditions. However, the opportunities to offer ancillary services to the power networks by the injection of reactive power are expected to be recognized in the near future and some grid support services can be required also during faults (i.e. faults ride-through (FRT) or low voltage ride-through (LVRT) capabilities) [4,7,8]. Consequently, the injection of the reactive power must be carefully taken into account and a detailed representation of the inverter control system is required when modeling the contribution of PV systems to the short-circuit currents [5].

Several simulation studies [9–15] have been conducted to perform extensive analysis of the dynamic performance of the PV systems under different fault conditions. In these studies the specific response of the inverter control system is taken into account. Despite of their advantage to include any influencing factor, these

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approaches require a full time-domain representation of the whole power system; then, they result to be time consuming, computationally intensive and may not be viable in power networks with a large penetration of PV systems.

As an alternative, analytical fault models of PV systems have also been proposed in literature with the aim to extend the conventional short-circuit analysis methods to networks with distributed generators (DGs). In [1] a model to estimate the fault contribution of PV systems using a current control scheme and operating at unity power factor has been presented. A model for inverter-interfaced DGs using a voltage control scheme has been proposed in [3]. In [5] an evaluation of the fault response of PV systems using active limitation of the filter inductor current has been developed. In [16] the fault behavior of the PV system has been modeled by a current injection equal to the maximum current flowing through to the inverter. With respect to time-domain simulation approaches, analytical methods avoid high computational burden; however, they introduce modeling approximations in the representation of PV systems. In particular, [1] does not include the actual effects of the reactive power injection on the short-circuit current; [3] assumes that the inverter internal voltage remains constant during faults; [5] does not consider all the influencing factors, although it might account for FRT capability; [16] does not accurately consider the phase angle of the current injected by the PV system during the fault.

This paper proposes a new analytical model of the fault contribution of three-phase PV systems equipped with voltage source converters (VSCs). Such a model allows to extend the classical steady-state short-circuit current calculation, based on the bus impedance matrix approach [17], to active balanced power networks including PV systems, with the aim to analyze their impact on the breaking capacity of the interrupting devices. The proposed model takes in account environmental conditions as well as VSC current limits. Also, it is able to represents the behavior of different VSC control systems and, then, to consider the real effects of reactive power injections. Finally, such a model can be easily integrated in a software package for power system analysis.

The paper is organized as follows. The configuration of the three-phase PV system and the logic of the VSC control system are briefly recalled in Section 2. In Section 3, starting from the time-domain analysis of the IEEE benchmark PV system in [10], firstly relations among the components of the VSC current in the *dq* reference frame and the logic of different types of VSC control systems are deduced; then, the expressions of the active and reactive powers injected by the PV system after the fault are derived. In Section 4, these expressions are included in the classical equations of the steady-state short-circuit analysis of balanced power networks. In Section 5, the proposed approach is validated by comparing analytical results with time-domain simulations of the IEEE benchmark PV system. Eventually, the proposed approach is used to analyze the impact of a large penetration of PV systems on the fault currents.

2. Three phase PV system configuration and control

The fault response is analyzed with reference to the IEEE benchmark PV system. It consists of a PV generator connected to the dc side of a VSC, which is interfaced with an utility grid at the point of common coupling (PCC) through a low pass filter and a LV/MV transformer, as shown in Fig. 1a. The control architecture is highly complex. In general, as shown in Fig. 1b, it is composed of:

(A) grid-synchronization control;
(B) current control; and
(C) active and reactive power controls.

Since the control system dictates the PV system response to faults, in the following its main characteristics are recalled. Details about the PV system configuration and control system can be found in [9–11].

2.1. Grid-synchronization control

The grid-synchronization control synchronizes the PV system with the utility grid, by providing the frequency ($\omega = 2\pi f$) of the VSC outputs and the phase angle θ, which is used for the transformation of the three-phase variables v_{ab}, v_{bc}, v_{ca} from the initial *abc* to the rotating *dq* reference-frame. In particular, it ensures that the *d*-axis component of the VSC terminal voltage v_d is aligned with the VSC terminal voltage $\overline{V}_{ab}$ (in the following the VSC terminal voltage will be denoted simply as $\overline{V}$); then, the *q*-axis component v_q results equal to zero.

2.2. Current control

The VSC adopts a current control scheme which presents the advantage of the direct regulation of the VSC current with respect to a voltage control scheme. The current control is the inner control loop of the VSC control system. It regulates the VSC terminal voltage $\overline{V}$ to be synthesized by the pulse-width modulation strategy (that transforms the modulating signals m_a, m_b, m_c in appropriate switching states) to a value that optimizes the active and reactive power production of the PV system. Such a task is accomplished in a rotating *dq* reference frame by the direct regulation of the *d*- and *q*-axis components of the VSC output current, i_d and i_q, to given set-points, i_d^* and i_q^*, respectively. In fact, as it is well known, in the *dq* reference frame i_d and i_q are related to the active power P and reactive power Q outgoing the low-pass filter inductors according to

$$P = \frac{3}{2}(v_d i_d + v_q i_q) \quad Q = \frac{3}{2}(v_q i_d - v_d i_q) \tag{1}$$

Since the grid-synchronization controller guarantees that $v_q = 0$, it results

$$P = \frac{3}{2} v_d i_d \quad Q = -\frac{3}{2} v_d i_q \tag{2}$$

Then, P and Q can separately be regulated to their set-points, P^* and Q^*, by regulating i_d and i_q to their set-points, i_d^* and i_q^*, respectively. Saturation blocks are implemented at this level so as to limit i_d and i_q to the values imposed by the VSC manufacturers to prevent thermal damage of power converters. In the following, such limits are indicated as I_d^* and I_q^* for the *d*- and *q*-axis current components, respectively; their values range from 1.2 to 2.0 p.u. [10].

2.3. Active and reactive power controls

The active and reactive power controls are the outer control loops of the VSC control system which separately determine the set-points P^* and Q^* for the inner control loop.

The active power set-point P^* is defined by the maximum power-point tracking (MPPT) and the dc-link voltage control schemes. At any sunlight and temperature condition, the MPPT extracts the maximum power P_{pv} generated by the PV panels by defining the set-point V_{dc}^* for the dc-link voltage V_{dc}; the dc-link voltage control scheme processes the error between V_{dc} and V_{dc}^* so as to determine the set-point P^*.

The reactive power set-point Q^* should be defined by a dedicated VAr or a voltage regulation control scheme so as to provide ancillary services to the utility grid [7]. Unfortunately, the capability of PV systems in VAr and voltage regulation has not seriously