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A comprehensive LVRT strategy of two-stage photovoltaic systems under balanced and unbalanced faults

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ABSTRACT

The increase in penetration of photovoltaic (PV) systems into utility grid poses great challenges in terms of system stability, thus, force several countries to update their grid codes to accommodate the low voltage ride-through (LVRT) capability of PV systems to stay connected to the grid and supply the reactive current to support grid voltage during grid faults. In line with this, a comprehensive LVRT strategy is proposed in this paper for grid-connected PV systems under balanced and unbalanced grid faults. The proposed strategy includes the power references calculation method to meet the requirements of grid codes, the active power reduction method to avoid the overvoltage of the dc-link, the peak current limiting method to avoid the overcurrent of the inverter, and three current reference generators implemented by the proposed current reference formulations to ensure the reliable operation of PV systems under different grid faults. The effectiveness of the proposed strategy has been verified in MATLAB/SIMULINK simulation platform and the results show that the proposed LVRT strategy has good performance under different grid faults.

1. Introduction

Power generation from renewable energy sources (RESs) has been increasing significantly due to environmental issues and continuous increase in energy demands worldwide [1–3]. Photovoltaic (PV) power generation system is one of the RESs which is growing exponentially and is expected to play a great role in the future power system due to decline in the PV panel prices with the advance in the technology [4,5].

As the penetration of PV systems increases, their impacts on the power quality, system security and stability are becoming a great concern and of immense importance to power system operators. Recognition of these impacts of high penetration PV systems paves the way for the development of new grid codes (GC) in several European countries and some Asian countries such as Japan and China to provide different ancillary services that increase system stability and power quality [4,6,7]. Low voltage ride-through (LVRT) capability, which requires the grid-interfaced distributed generation (DG) systems, including PV system, to stay connected during low voltage resulted from grid faults, is one of these services to maintain and improve the grid stability. Furthermore, the GCs also requires the PV system to support the grid voltage by injecting the necessary reactive current, which is a function of voltage dip that can be as large as full rated current when voltage dip is below 50% [8].

Nowadays, the two-stage PV system is widely used around the world since it includes a boost dc-dc converter to step up low voltage of PV arrays and to perform the maximum power point tracking (MPPT) function, and a two-level three-phase voltage source inverter (VSI) to implement different functionalities including the grid current controlling and the LVRT capabilities. The independent control of the MPPT and the generated power qualities, by dc-dc converter and the VSI, respectively, which allows the flexible control of PV modules/strings are the major advantages of two-stage PV systems. In addition, achievement of higher efficiency and better utilization of PV systems, especially under partial shading conditions, are also the advantages of two-stage PV systems. At the same time, PV arrays can operate in larger voltage ranges because of the boost performance of dc-dc converter, which in turn allows the designer to choose the dc-link voltage and the capacitor size flexibly [9].

Control strategies for LVRT capability of two-stage PV systems have been identified, but they have not been studied comprehensively. A multi-mode operation with LVRT capability for three-phase PV power system was reported in [10] and controller strategies during grid faults for single- and two-stage PV system were developed and different protection issues were discussed in [11]. In [12] a reactive power controller based on probabilistic wavelet fuzzy neural network was presented to offer LVRT capability for PV systems. All these references on two-stage PV systems mainly focused on developing and designing controllers for dc-dc boost converters during grid faults to avoid dc-

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voltage increase without giving much consideration on other aspects of LVRT capabilities. In addition to these references on two-stage PV systems, several effective control schemes have been proposed highlighting different power quality features during unbalanced grid faults [13,14]. Furthermore, in [15], the space vector Fourier transform (SVFT)-based control techniques for fault ride-through under unbalanced grid faults for single-stage PV system were proposed, which was implemented in α-β stationary frame. However, the proposed method in [15] considered only the injection of positive sequence currents, implemented for single-stage PV system, and neglected the variation of the dc-link voltage, which inevitably needs to be considered for two-stage PV systems. Moreover, LVRT control for single-stage inverter-based grid-connected photovoltaic power plant according to Malaysian grid code in [16] worth mentioning. Even though the authors in [16]considered the problem associated with dc-link voltage increase, their work only considered the injection of positive sequence currents during grid faults.

On this basis, this paper proposes a comprehensive LVRT control scheme, which provides grid support through the injection of reactive power under balanced and unbalanced grid faults, for two-stage grid-connected PV systems. The main contributions of this paper are listed as follows: 1) A detailed formulation of novel current reference generators in dq-frame is proposed for flexible power quality control during balanced and unbalanced LVRT process; 2) A power reduction method is proposed to avoid the overvoltage of the dc-link during grid faults; 3) The active and reactive power control strategies are formulated and the respective controllers are implemented with flexible power quality control and peak current limiting capability, for effective implementation of LVRT.

This paper is organized as follows. Section 2 describes the modeling of two-stage PV systems. In Section 3, the proposed control scheme under grid faults is explained. Simulation results in Section 4 show the performance of the proposed controller. Finally, the conclusions of the paper are summarized.

2. Description of grid-connected PV system structure and component modeling

Fig. 1 illustrates the schematic diagram of a representative two-stage grid-connected PV system. It consists of a PV generator comprising of several PV modules connected to dc-dc converter which in turn connected to the dc side of a two-level three-phase VSI. The PV system is interfaced with the grid at the point of common coupling (PCC), on the ac side of the VSI, through an output LCL filter.

The PV array can be modeled as single diode equivalent circuit containing a current source, an anti-parallel diode, a series and a shunt resistance, which can be found in [17–21].

As mentioned earlier, the interfacing unit employed for a two-stage grid-connected PV system is the cascaded connection of a boost dc-dc converter and two-level three-phase VSI.

The boost dc-dc converter produces a constant output dc voltage that is greater than its input dc voltage from unregulated dc source, PV array. It uses pulse-width modulation (PWM) technique to control the output dc voltage by regularly matching the characteristic of the PV system to the equivalent load, dc bus of the inverter, by varying the duty cycle of the boost converter switch [18,22,23].

The two-level three phase VSI [24,25] is commonly used in grid-connected PV system to convert the dc voltage to three phase ac voltages by employing appropriate modulation scheme to generate proper switching pulses [22,26,27].

The mathematical model of the three-phase VSI for a balanced three-phase system can be developed by considering the VSI as an ideal voltage source at the fundamental frequency. The cascaded connection of the dc-link capacitor, VSI, LCL-filter, and a grid is modeled in the dq-reference frame using space-phasors [28] by neglecting the dynamics of filter capacitor, thus, at the fundamental frequency, the filter is considered as an L-filter with total inductor L_T and equivalent series resistance (ESR) of R_T and the transformer voltage at low voltage (LV) side is considered as the grid voltage at the PCC. Thus, the dynamics of ac-side of the VSI in Fig. 1 is represented by the following space-phasor equation [29]:

$$L_T d\vec{i}/dt = -R_T\vec{i} - \vec{v_c} + \vec{v} \tag{1}$$

where $\vec{i}$ represents the inverter current, $\vec{v_c}$ is the PCC voltage, $\vec{v} = \frac{v_{dc}}{2}m$ is inverter voltage, v_{dc} is the dc-link voltage, and $\vec{m}$ is the modulation index vector.

The dynamic equation of the dc-link capacitor voltage for the lossless system, using power balance equation among capacitor, PV and grid can be expressed as:

$$(C_{dc}/2)dv_{dc}^2/dt = P_{pv} - P_{inj} \tag{2}$$

where P_{pv} and P_{inj} are powers produced by PV array and injected into the grid, respectively.

The state-space model of the system in (1) in the dq-frame and (2) along with boost converter model form the overall system model that provides a comprehensive dynamic model of a two-stage grid-connected PV system which is used for feedback control design.

3. Proposed control strategy during grid faults

3.1. Framework of the proposed control strategy

The current injected at the PCC determines the behavior of the three-phase inverter under grid faults. Thus, an appropriate control strategy that enables the inverter to ride through voltage dips during grid faults is crucial. The GCs for grid connected PV systems underlines the injection of reactive power during grid faults to enhance grid stability.

Fig. 2 depicts the block diagram of proposed control scheme for a two-stage grid-connected PV system with LVRT capability during grid faults. The system controller takes the measured phase voltages $\vec{v_c}$ at the PCC, the converter side inductor currents $\vec{i}$, the dc-link voltagev_{dc}, the PV array voltagev_{pv}, and the PV array current i_{pv} as inputs. The three-phase ac voltages and currents are transformed into the dq-frame and decomposed into their respective symmetric components, using a sequence separation method, provided by Fault Detection, PLL and Sequence Separation Method (SSM) block. In addition, this block calculates the voltage level according to (3) and also determines the

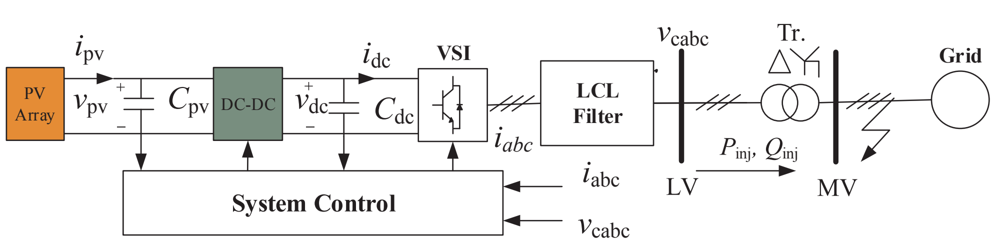

Fig. 1. Single-line diagram of a two-stage grid-connected PV system.