LOW-VOLTAGE RIDE-THROUGH CONTROL STRATEGY OF PV SYSTEM BASED ON ACTIVE AND REACTIVE POWER CONTROL

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ABSTRACT

This paper presents a novel control strategy of the two-stage three-phase photovoltaic (PV) system based on the active and reactive power control to improve the low-voltage ride-through (LVRT) capability. With the help of the new strategy, the PV array can generate the appropriate active power according to the depth of the grid voltage dip to restrain the over-voltage and over-current. Simultaneously, the proposed strategy can ensure the reactive power support to help the voltage recovery. Besides, a feed forward compensation is used to smooth the DC-link voltage fluctuations during the grid fault. The effectiveness of the proposed control strategy is verified through various simulation scenarios when different grid voltage drop depths occur. The proposed control strategy can not only enhance the LVRT capability of the PV system, but also provide the reactive power support.

Keywords: Low-voltage ride-through, photovoltaic system, reactive power, grid inverter

1 INTRODUCTION

In recent years, the grid-connected photovoltaic (PV) generation systems capacity has been increased significantly that their dynamic behavior is of a notable impact on the security and reliability of the power system during voltage dips [1]. For this reason, it is required that the PV system should stay connected to the grid during voltage dips, and this ability is termed as the low-voltage ride-through capability.

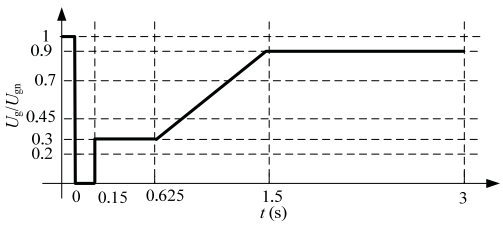
Among the existing control methods, the chopper circuit with a resistor across the DC bus is the mostly used one [2]. But this strategy does not have the ability to provide reactive power support to the grid. Moreover, with extra hardware the chopper circuit will not only increase the costs but also decrease the system reliability.

Recently, some new low-voltage ride-through (LVRT) methods have been proposed to reduce the amplitude of the output current of the inverter as well as the DC-link over-voltage during the faults. The literature [3] pays attention to improving the quality of the output waveform of the PV system in the low voltage duration, but ignores the reactive power support requirement. In [4] and [5], the reference current values of the Boost circuit and the grid inverter are changed to realize the LVRT during the voltage dip. Based on the single-phase PQ theory and the PR control scheme, a LVRT control method is proposed for the single-stage single-phase photovoltaic system in [6]. However, the most stringent status named the zero voltage ride-through (ZVRT) is not discussed in all the references mentioned above.

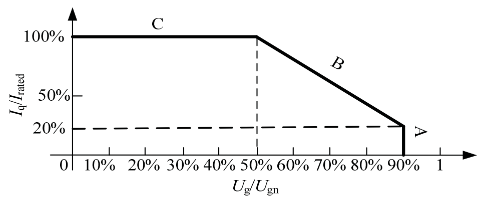
In [7] we proposed an advanced control strategy for both the DC/DC converter and the grid-connected inverter to improve the LVRT capacity of the two-stage three-phase PV system. However, this method provides zero active power when the grid voltage drops more than 50% of its normal value, which will reduce the efficiency of the PV array utilization during the fault. In this paper, the active power reference depends on the depth of the voltage dip rather than the reactive power reference once the voltage drops more than 50% of its normal value. Compared with the conventional methods, the simulation results show that the proposed control strategy can not only enhance the LVRT capability of the PV system, but also provide grid support through the power control without additional device. Compared with the literature [7], the proposed control method can afford a certain amount of active power to increase the utilization of the PV array when the grid voltage drops more than 50% of its normal value.

2. GRID CODES OF LVRT

Among the different grid codes of LVRT, the most widely adopted one is the E.ON code which is proposed by Germany [4, 5]. Fig. 1 (a) shows the LVRT requirement of the distributed generation (DG), where the DG should keep connected to the grid when the system operates in the area above the curve. At the same time, the system should inject appropriate reactive current to support the grid recovery according to Fig. 1(b).



(a)



(b)

Fig. 1: The E.ON code (a) The LVRT requirement, (b) The reactive current requirement.

3. MODELING OF THE TWO-STAGE THREE-PHASE PV SYSTEM

The schematic diagram of the two-stage three-phase PV system is shown in Fig. 2. The grid system contains the PV panels, the Boost circuit, the three-phase inverter and the control system. The control system is composed of two control levels including the Boost circuit control and the grid inverter control. A detailed dynamic model of the PV system will be introduced below.

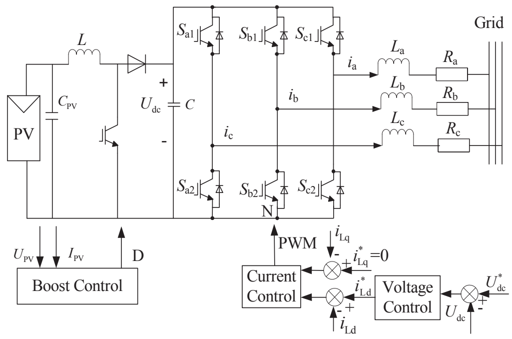


Fig. 2: Schematic diagram of the PV system

3.1 Mathematical Model of PV

Considering the practical application, the PV characteristic is usually converted to an explicit formula with the precondition of accuracy insurance [8].

$$I_{PV}=I_{sc}[1\text{-}C_1(e^{\frac{U_{PV}}{C_2U_{oc}}}\text{-}1)] \tag{1}$$

where $C_1=(1\text{-}\frac{I_m}{I_{sc}})e^{\frac{-U_m}{C_2U_{oc}}}$, $C_2=(\frac{U_m}{U_{oc}}\text{-}1)[\ln(1\text{-}\frac{I_m}{I_{sc}})]^{-1}$.

3.2 Mathematical Model of Grid Inverter

The equations of the grid inverter can be given in a *d-q* frame rotating at the line frequency.

$$\begin{cases} L\dfrac{di_{Ld}}{dt}+Ri_{Ld}-\omega Li_{Lq}=d_dU_{dc}-u_{gd} \\ L\dfrac{di_{Lq}}{dt}+Ri_{Lq}+\omega Li_{Ld}=d_qU_{dc}-u_{gq} \\ C\dfrac{dU_{dc}}{dt}=\dfrac{U_{dc}}{R}-\dfrac{3}{2}(d_di_{Ld}+d_qi_{Lq}) \end{cases} \tag{2}$$

where $\mathbf{i}_L=i_{Ld}+ji_{Lq}$ is the output current vector of the grid inverter; $\mathbf{d}=d_d+jd_q$ is the inverter duty cycle vector; $\mathbf{u}_g=u_{gd}+ju_{gq}$ is the grid voltage vector; and the U_{dc} is the DC bus voltage.

3.3 Control Strategy in Normal Operation

The boost circuit controls the output power of the PV array and boosts the voltage to an appropriate level so that the grid inverter could work regularly. In order to track the PV array optimum operating point, the hill climbing method, which is widely used in industrial applications due to its simplicity and feasibility, is used in this paper.

The grid inverter controls the DC-link voltage and delivers the necessary current to the grid through the multiple-loop control of voltage and current. The detailed scheme can be found in [7].

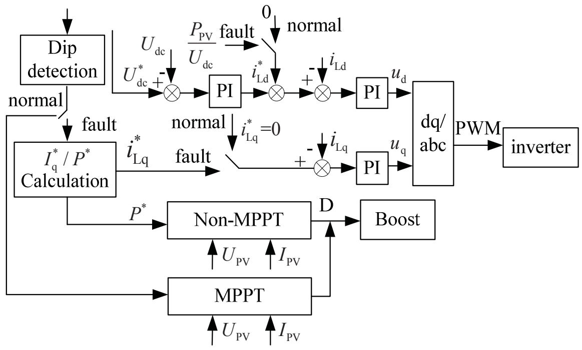


Fig.3: Schematic diagram of the PV system

4. PROPOSED LOW VOLTAGE RIDE THROUGH STRATEGY

When a low voltage fault occurs, the incoming power from the PV array and the power flowing into the grid are imbalanced which will lead to transient excessive voltage at DC-side and over-current at AC-side. Therefore, the LVRT strategy is introduced to ensure that the PV system can keep connected to the fault grid by decreasing both the DC-link voltage and the inductive current. Moreover, the reactive power is also provided to help the grid voltage recovery.

The control scheme of the proposed LVRT strategy is shown in Fig. 3. It contains the grid fault detection, the power calculation, the output power controller for the PV array and the grid inverter controller. The PV system operates in the MPPT mode under the normal situation. When the grid voltage sag is detected, the PV array will switch to the Non-MPPT operation mode and generate the appropriate active power according to the depth of the voltage sag to keep the power balance of the system. In addition, the grid inverter will provide the required reactive current to help the voltage recovery. In order to smooth the fluctuations of the DC-link voltage, a feed forward compensation term is applied in the DC-link voltage control [9, 10]. It is worth to point out that a new active power reference calculation method is proposed in this paper which is the most different from the literature [7]. The active power reference relates to the depth of the grid voltage dip in the proposed method which can ensure the active power transmission in the system when the grid voltage drops less than 50% of its normal value.

4.1 Gird Fault Detection

In this paper, the Root Mean Square (RMS) method, which can be easily obtained without additional transformation, is adopted to detect the grid fault. The voltage can be given by

$$U_g = \sqrt{U_{gd}^2 + U_{gq}^2} \tag{3}$$

where U_{gd} is the active component of the grid voltage while $U_{gq}$is the reactive one.

4.2 Reactive Power Calculation and Control

As the control reference, the specified reactive current calculation is the key to meet the LVRT requirements during the grid voltage dip as shown in Fig. 1(b). According to Fig. 1(b), the required reactive current I_q^* during the fault can be expressed piecewise corresponding to the line A, B and C, respectively.

$$I_q^* = \begin{cases} 0 & U_g > 0.9U_{gn} \\ I_{rated}(2\text{-}2\dfrac{U_g}{U_{gn}}) & 0.9U_{gn} \geq U_g > 0.5U_{gn} \\ I_{rated} & U_g \leq 0.5U_{gn} \end{cases} \tag{4}$$

where U_g and U_{gn} are the amplitude of the present and the normal grid voltage, respectively [2,7], I_{rated} is the rated current of the grid inverter.

In normal operation, the reactive power reference of the grid inverter is kept zero in order to achieve unity power factor. However, during the grid fault, the reference value of the reactive current will be set according to Eq. (4).

4.3 Active Power Calculation and Control

In order to protect the system from both the over-current and over-voltage, the active power flowing into the PV system should be restrained.

When the grid voltage value is more than 50% of its normal value, the maximum allowed active power flowing through the grid inverter during faults can be obtained [7]

$$P^* = \frac{3}{2} U_{\mathrm{g}} I_{\mathrm{rated}} * \sqrt{1 - I_{\mathrm{qratio}}^2} \quad (5)$$

where $I_{\mathrm{qratio}} = I_{\mathrm{q}}^*/I_{\mathrm{rated}}$ which can be calculated by Eq. (4).

When the grid voltage value is less than 50% of its normal value, the active power can be obtained by the Eq. (6) for improving the utilization of the PV array during grid faults.

$$P^* = \frac{3}{2} U_{\mathrm{g}} I_{\mathrm{p}} = \tau \frac{3U_{\mathrm{g}}^2}{2U_{\mathrm{gn}}} I_{\mathrm{rated}} \quad (6)$$

where the factor $\tau \in [0,1]$. Considering a large τ may increase the current, the typical value, 0–0.5, is chosen [10].

During the grid voltage fault, the boost circuit controller switches from the MPPT mode to the Non-MPPT mode by setting the reference value of the PV array output power as P^* calculated by Eq. (5) or Eq.(6). Therefore, the imbalanced energy flowing through the PV system can be reduced. Moreover, the PV system will continue the active power production during faults even when the voltage drops more than 50% of its nominal value, which can increase the energy captured from the PV array.

4.4 Feed forward Compensation Control

When the grid voltage dips, the DC side input current may not be equal to the output current, leading to the fluctuation of the DC-link voltage. In order to smooth the fluctuation, the item $P_{\mathrm{PV}}/U_{\mathrm{dc}}$, reflecting the instantaneous current injecting into the DC-link from the PV array, is used as the compensation, where P_{PV} is the instantaneous power injecting into the DC-link from the PV array and U_{dc} is the voltage across the DC-link capacitor.

5. ANALYSIS OF LOW VOLTAGE RIDE THOUGH STRATEGIES

The complete PV system model as shown in Fig. 2 has been established and simulated in Matlab/Simulink. The simulations are conducted on a 500 kW grid-connected PV system and the main parameters of the studied system are listed in Table 1. The detailed parameters can be found in [7]. For comparisons, three different control strategies of LVRT, the conventional strategy using DC-link chopper circuit (named strategy A), the control strategy in literature [7] (named strategy B) and the proposed method (named strategy C), are investigated for two different situations (the grid voltage drops to 0 for 150ms and 30% of its normal value for 625 ms).

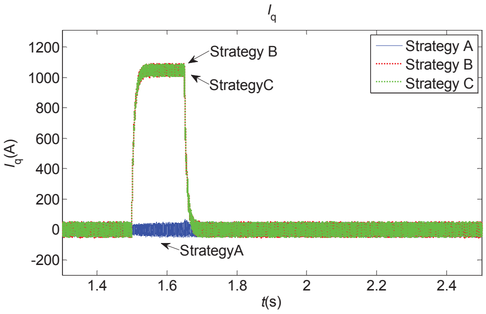
TABLE 1: Parameters of the PV system

Maximum power of the PV cell	P_{m} =245W
Serial number of the PV array	N_{s}=20
Parallel number of the PV array	N_{p}=102
Grid voltage of the inverter	U_{g}=380V
DC-link voltage	U_{dc}=750V
DC-link capacitor	C_{dc}=0.03F
Grid frequency	ω=100πrad/s
LR filter of the inverter	L=0.51mH, R=0.66mΩ
Switching frequency of inverter	f=2k Hz
Inductor of the boost converter	L_{B}=2mH
Switching frequency of boost	f_{B}=2k Hz

5.1 ZVRT

Considering the worst situation, the point of common coupling (PCC) voltage drops to 0 at 1.5s and lasts for 150 ms. The transient responses of the PV system with strategy A, B and C are shown in Fig. 4.

Fig. 4(a) shows that compared to the conventional control, both the strategy B and C are able to provide corresponding reactive current which is helpful for the voltage recovery. The active power under the three control strategy is zero as shown in Fig. 4(b). Fig. 4(c) and Fig. 4(d) show that these three control strategies can reduce the value of transient current and the DC-link voltage, and realize ZVRT. Obviously, with the control strategy B and C, the PV system has better LVRT behaviors than the cases with the conventional strategy A.



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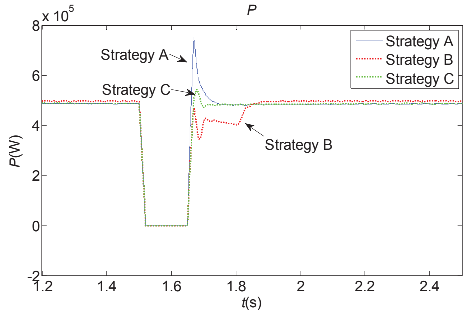

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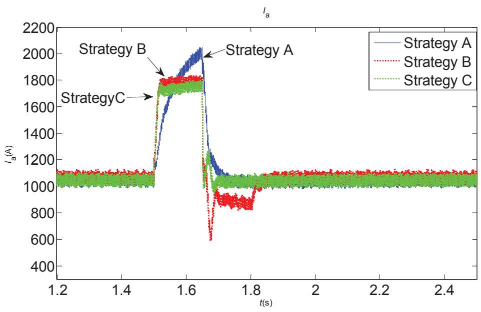

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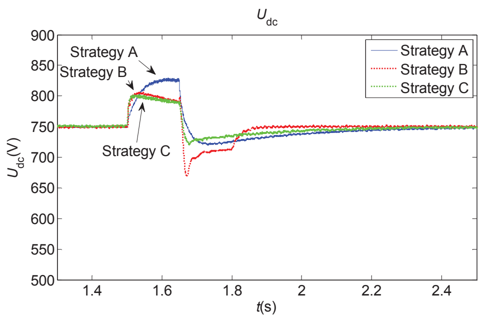
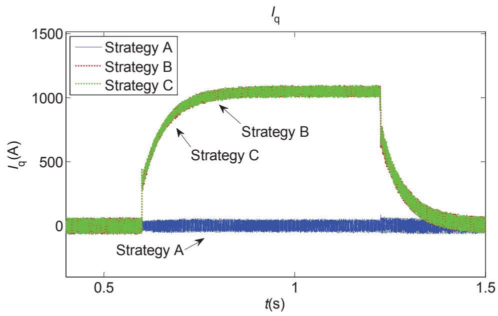


(d)

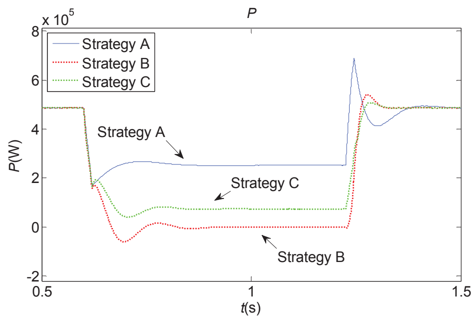
Fig.4: Simulation results with the zero voltage fault (a) Reactive current, (b) Active power, (c) Magnitude of the grid side current (d) DC-link voltage.

5.2 LVRT

The situation in Fig. 5 shows a grid fault with 70% voltage drop and 625ms duration. The reactive power and the active power with the three control strategy are shown in Fig. 5(a) and (b), respectively. It is observed that both the strategy B and C can provide corresponding reactive current while the conventional method provides zero. Moreover, the proposed method can provide more active power than the method mentioned in [7] during grid voltage faults, and this can improve the efficiency of the PV array utilization. In Fig. 5(c) and (d), with the strategy B and C, the PV system has lower over-current and lower over-voltage than with the strategy A at the stage of voltage sag. Due to the more active power provided, the peak current and peak voltage with the strategy C are slightly larger than with the strategy B, but still less than the upper limit of the over-voltage and over-current [10].



(a)



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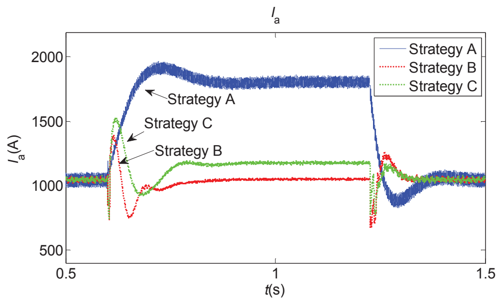

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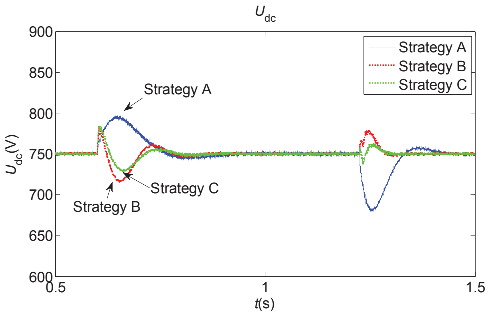

(d)

Fig.5: Simulation results with the 70% voltage dip (a) Reactive current, (b) Active power, (c) Magnitude of the grid side current (d) DC-link voltage.

6. CONCLUSIONS

On the basis of the E.ON code proposed by Germany, a novel low-voltage ride-through control strategy of the two-stage three-phase photovoltaic system is proposed in this paper. The control strategy enables the zero-voltage ride-through and could improve the low voltage ride through capability of the PV system by operating in different modes according to the depth of the grid voltage dip.

The simulation results show that the proposed control strategy could effectively keep power balance between the two sides of the inverter to eliminate the over-voltage and the over-current of the two-stage three-phase photovoltaic system and provide the required reactive power support during the grid fault. Compared with the conventional protection, the new method performs better transient behaviors and can fulfill stringent grid code requirements during various low voltage events without additional device.

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