A new control strategy for low-voltage ride-through of three-phase grid-connected PV systems

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Abstract: Power quality and current limitation are the most important aspects of the grid-connected power converters under fault. Since the distributed energy resources are widely used, fault management strategy is important for micro-grids applications. This paper presents a new control strategy for low-voltage ride-through for 3-phase grid-connected photovoltaic systems. The proposed method, which is designed in a synchronous frame using positive and negative sequence components, can protect the inverter from overcurrent failure under both symmetrical and unsymmetrical faults and provides reactive power support. The method does not require a hard switch to switch from MPPT to a non-MPPT algorithm, which ensures a smooth transition.

1 Introduction

During the last decades, the use of distributed energy resources (DERs) has increased due to economical, technical and environment concerns [1, 2]. Micro-grids (MGs) have emerged as a potential solution for integrating DERs into the distribution networks operating in grid-connected mode [3]. Photovoltaic (PV) generation as the commonly used DERs should contribute to the grid stability by providing high-quality services, beyond the basic power delivery [4–7]. According to the recently revised grid codes, PV systems are supposed to stay in grid-connected mode during faults [8]. When a fault occurs, the converter should have a quick response to the disturbance to eliminate the effect on the inverter and the grid. Furthermore, a certain amount of reactive power needs to be injected to support the grid when a low voltage fault is occurred [9]. This capability is known as low voltage ride-through (LVRT).

Different methods have been presented in the literature. For example, in [3], a control strategy for limiting the inverter current based on an islanded system is presented. However, the LVRT strategy in grid-connected PV is a big challenge. From simulation test, the dynamics of the PV array (including Maximum Power Point Tracking (MPPT) algorithm), the capacitive dc-link voltage, and the grid. Furthermore, a certain amount of reactive power needs to be injected to support the grid when a low voltage fault is occurred [9]. This capability is known as low voltage ride-through (LVRT).

In light of the above, the proposed LVRT scheme in this paper is able to:

(1) Operate for both symmetrical and unsymmetrical faults.

(2) Limit the current to 2 pu during 3-phase fault without activating the inverter overcurrent protection.

(3) Limit the current to 1.5 pu during unbalanced faults.

(4) Provide high quality sinusoidal voltage and current during all types of faults.

(5) Eliminate the need to switch from MPPT mode to non-MPPT mode.

The proposed LVRT scheme is presented, including the method to estimate the positive sequence and negative sequence components for voltage and current in the synchronous frame, voltage loop design with the proposed current limiting strategy, reactive power injection and current loop design. The proposed control strategy is verified by MATLAB/Simulink simulations in Section 3. Finally, conclusions are drown at the end to summarise the advantage of the proposed method in Section 4.

2 Proposed control strategy

The system under study plus the proposed LVRT strategy are illustrated in Fig. 1. The proposed control strategy uses the classic cascaded voltage and current loops in dq-frame, which includes a proposed Voltage Compensation Calculation (VCC) unit (detailed in Fig. 2). The current loop consists of four PI controllers for d-q currents in positive (i_{dp}, i_{dq}) and negative (i_{dn}, i_{dq}) sequences (see Fig. 3). The Delayed Signal Cancellation (DSC) method, explained in [12], is used to get the symmetrical components of the inverter voltage V_{inv} and inverter current I_{inv}, while a DSC-PLL, which introduced in [13] synchronises the system with the grid. A reactive power injection block is proposed, which determined how much reactive power should be injected during fault. The proposed scheme is detailed below:

2.1 Symmetrical components generation

In this paper, the well-known method of DSC is used for sequence component separation. The DSC method, which is detailed in [12], uses:

\begin{align}
V_{paa, \beta} &= \frac{1}{2} \left[ V_{aa, \beta} + j V_{ab, \beta} \left( t - \frac{T}{4} \right) \right] \\
V_{nna, \beta} &= \frac{1}{2} \left[ V_{aa, \beta} + j V_{ab, \beta} \left( t - \frac{T}{4} \right) \right]
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\end{align}
In (1) and (2), $V_{p}(\alpha, \beta)$ and $V_{n}(\alpha, \beta)$ are the estimations of the positive and negative sequence signals in the stationary frame; $T$ is the signal period, which is the same as the grid period. The symmetrical components for current can be estimated using (1) and (2) as well. Then both voltage and current signals are converted to the synchronous frame using the standard Park Transform.

### 2.2 Voltage loop with voltage compensation calculation

Since the control strategy aims to limit the inverter current during balanced and unbalanced faults while the PV array is still running without disabling the MPPT, the proposed VCC unit is applied. As it is shown in Fig. 2, the proposed VCC unit determines the reference DC-link voltage $V_{dc}^{*}$ through adding a compensation value $V_{com}$ to the optimum value $V_{opt}$ provided by the MPPT algorithm. The amended DC-link reference voltage $V_{dc}^{*}$ determines the reference d-component current $I_{d}^{*}$ through a standard voltage loop using a PI controller. The VCC is designed to force the PV array to produce less power during fault compared to the steady state operation. As it can be seen from $P_{pv}$-$V_{pv}$ characteristic in Fig. 4, it is possible to reduce $P_{pv}$ through either adding $V_{com}$ to $V_{opt}$ or subtracting $V_{com}$ from $V_{opt}$, respectively.

However, considering the $I_{pv}$-$V_{pv}$ curve, it can be easily found that only when the PV is operating at the right side of the MPP (Shadowed Area), the output current of the PV can be reduced i.e. when $V_{com}$ is added to $V_{opt}$:

$$V_{dc}^{*} = V_{opt} + V_{com} \quad (3)$$

For example, through using (3), therefore, when a fault occurs, the system will be operating at the fault operation point (FOP) shown in Fig. 4, where both $P_{pv}$ and $I_{pv}$ are reduced, leading to a reduced inverter current. In addition, the system is stable when the operation point is located at the right side of the MPP [14].

The VCC should be designed based on the following principles:

1. The VCC should force the PV system to reduce its active power generated during faults without interrupting MPPT during normal operation.
2. The VCC should be able to obtain the operation point located at the right side of the MPP.

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**Fig. 1** System under study plus the proposed control scheme for grid-connected PV

**Fig. 2** Structure of the proposed voltage compensation calculation unit

**Fig. 3** Current loop

In (1) and (2), $V_{p}(\alpha, \beta)$, $V_{n}(\alpha, \beta)$ are the estimations of the positive and negative sequence signals in the stationary frame; $T$ is the signal period, which is the same as the grid period. The symmetrical components for current can be estimated using (1) and (2) as well. Then both voltage and current signals are converted to the synchronous frame using the standard Park Transform.
(3) The VCC should have a quick response when the voltage sag is severe and slow response when the voltage drop is slight. This is because if the VCC has a quick response to a slow and small disturbance, the active power of the inverter will become unstable. This is achieved through introducing the quadratic functions illustrated in Fig. 2.

As shown in Fig. 2, both positive and negative sequences of Vinv d-component (Vdp, Vdn) are used in this proposed method. Vcom is calculated by both Vcom-p and Vcom-n, where Vcom-p and Vcom-n are generated by Vdp and Vdn variations, respectively. Vdp is 1 pu during normal operation and decreases after both symmetrical and unsymmetrical faults. Considering 10% tolerant, Vcom-p can be calculated as (4):

\[ V_{\text{com-p}} = -\Delta V_{\text{dp}}(V_{\text{dp}} - 0.9) \]  (4)

where \( \Delta V_{\text{dp}} \) is the voltage sag of Vdp. Using (4), which is simply the quadratic curve shown in Fig. 2, leads to a higher rate of increase in Vcom-p as \( \Delta V_{\text{dp}} \) increases. On the other hand, Vdn, which is zero during normal operation, decreases following only unsymmetrical faults. Considering 10% tolerant, Vcom-n can be calculated as (5):

\[ V_{\text{com-n}} = \Delta V_{\text{dn}}(V_{\text{dn}} - 0.1) \]  (5)

where \( \Delta V_{\text{dn}} \) is the voltage sag of Vdn. Using (5) leads to a higher rate of increase in Vcom-n as \( \Delta V_{\text{dn}} \) increases. Note that Vcom-n is negative and \( \Delta V_{\text{dn}} \) is positive. Both Vcom-p and Vcom-n are limited to \( V_{\text{oc}} - V_{\text{opt-max}} \). where \( V_{\text{oc}} \) is the PV array open circuit voltage and \( V_{\text{opt-max}} \) is the \( V_{\text{opt}} \) at 1 pu solar power. By doing this, it is ensured that \( V_{\text{dc}} \) remains smaller than \( \frac{V_{\text{dc}}}{2} \). Since in the simulated model \( V_{\text{dc}} - V_{\text{opt-max}} = 0.2 \) pu, 0.2 pu is used in Fig. 2. Thus, from (4) and (5), when both Vdp and Vdn sags depth under 0.5 pu, Vcom-p and Vcom-n will reach the limitation (0.2 pu), Vcom will be calculated through using Root-Mean-Square Deviation (RMSD) of the positive and negative sequence compensation terms Vcom-p and Vcom-n in order to ensure that Vcom remains under 0.2 pu as well. A Low-Pass-Filter (LPF) is used to add dynamics to the system, which reduces the oscillations at the fault occurring and clearing instances. A classic PI controller is used for the voltage loop to get \( I_{G} \), which is the reference d-component current.

2.3 Reactive power injection

Considering the grid standard of each country present in [8], Fig. 5 depicts how much reactive power must be injected in respect to the voltage sag in different countries. According to [15], a PV plant must be equipped with reactive power control function capable of controlling the reactive power supplied by the PV power plant. Since the DSC-PLL keeps the positive sequence of \( V_{\text{inv}} \) q-component \( V_{\text{qp}} \) at (at steady state), the negative sequence \( V_{\text{qn}} \) is proposed for reactive power regulation. \( V_{\text{qn}} = 0 \) during normal operation, thus, as \( V_{\text{qn}} \) increases after a fault, the reference \( I_{Q} \) increases. This paper uses the Chinese standard such that for \( V_{\text{qn}} < 0.1 \) pu; \( I_{Q} = 0 \), for \( V_{\text{qn}} > 0.8 \) pu, \( I_{Q} = 1.05 \) pu and \( 0.1 < V_{\text{qn}} < 0.8 \) pu, \( I_{Q} \) varies linearly.

2.4 Current loop

As illustrated in Fig. 3, the current loop consists of four classic PI controllers for positive and negative sequences of \( d- \) and \( q- \) components. The modulating signal \( m \) is calculated through adding the positive and negative modulating signals \( m = m_{p} + m_{n} \), while \( m_{p} \) and \( m_{n} \) are calculated through using the inverse Park transform. It is noted that the phase angle used in the negative channel is \( -\theta \).

The integral gain of the PI controllers is designed using the characteristic equation:

\[
\frac{\omega_{p}}{2} = \frac{K_{p}}{2L_{f}} \]  (6)

In (6), \( R_{f} \) and \( L_{f} \) are the LC filter impedance. Choosing the bandwidth to be \( 1759 \) rad/s (\( f_{s} = 280 \) Hz), the integral gain \( K_{i} = L_{f}R_{f} \omega_{p}^{2} = 9234.67 \). Considering the PI controller should be robust enough when fault occurs, from (6) the proportional gain \( K_{p} \) can be designed as follow:

\[
s^{2} + \frac{R_{f}}{L_{f}}s + \frac{K_{i}}{L_{f}} = 0
\]

\[
s^{2} + \frac{R_{f}}{L_{f}}s + \frac{K_{i}}{L_{f}} = \frac{K_{p}}{L_{f}}s + 1 = \frac{K_{p}}{L_{f}}s + \frac{K_{i}}{L_{f}}
\]

Equation (7) is basically the characteristic equation, thus, from the definition of a characteristic equation, the equivalent Open Loop Transfer Function (OLTFT) for this proposed control plant, which contains the open loop gain \( K_{p} \), is (the proportional gain of the current loop) can be written as (8):

\[
OPLF = \frac{K_{p}}{s^{2} + \frac{R_{f}}{L_{f}}s + \frac{K_{i}}{L_{f}}}
\]  (8)

where \( K_{i} \) is calculated above. The Root locus chart can be drawn based on \( K_{p} \). Fig. 6 is the Root locus diagram of this proposed current loop. Normally \( K_{p} \) is chosen smaller than 9.83, which is the critically damping point (\( \xi \)). However, here \( K_{p} = 82.5 \), where \( \xi \).
1 is used to enhance the system robustness during fault. Note that this high proportional gain will not affect the system's stability, which can be seen from Fig. 6. Also, the operation of the system when irradiation is varied will not be affected by this $K_p$.

### 3 Simulation results and analysis

In this section, the proposed control strategy is simulated in MATLAB/SIMULINK environment. The frequency of the grid is $f = 50$ Hz. The rest of the parameters are shown in Table 1. Note that all results are presented in pu based on $P_{rating} = 1$ pu.

Both symmetrical and unsymmetrical faults are simulated. For all the simulation, the fault occurs at $t = 1$ s and lasts for 0.2 s.

#### 3.1 Results under 3-phase to ground fault

Fig. 7 shows both the 3-phase voltage $V_{inv}$ and current $I_{inv}$ and the DC-link voltage with the conventional control strategy i.e. no LVRT strategy. As it can be seen, once the fault occurs, the 3-phase voltage $V_{inv}$ falls to almost zero, and 3-phase current $I_{inv}$ increases dramatically ($I_{inv}$ is much higher than 2 pu hard limit during the whole fault period, which will result to an overcurrent failure for the inverter). However, as shown in Fig. 8 with the proposed controller, the 3-phase currents $I_{inv}$ hit the hard limit for only less than 0.02 s. Then it is reduced to less than 2 pu. Note that the inverter protection system will not be activated during such a short period of time. The power generated by the PV array is reduced after fault, thus, the active power of the inverter is reduced. After the fault is cleared, the PV system will restore its normal operation.

#### 3.2 Results under double line (DL) fault

Fig. 9 shows the simulation results for a double line fault using the proposed method. As it can be seen, the proposed method reduces $P_{pv}$ through increasing $V_{dc}$, which results to $I_{inv}$ limited to less than 1.5 pu. Since the voltage on the healthy phase remains at 1 pu and both $I_{inv}$ and $V_{inv}$ remain sinusoidal during the fault, it is possible to keep feeding the loads connected to the healthy phase. The normal operation is restored as soon as the fault is being cleared.

#### 3.3 Results under single line to ground (LG) fault

Fig. 10 shows the simulation results for a single line to ground fault using the proposed strategy. Since the voltage on the two healthy phases remains at 1 pu during fault, the 3-phase voltage drop is slightly less than 3-phase fault and DL fault. Therefore, $V_{com}$, which is calculated by the VCC is smaller than the other types of fault, leading to $P_{inv}$ falls not significantly (almost remain at 1 pu). Meanwhile, $I_{inv}$ is limited to less than 1.5 pu without hitting the hard limit.

### Table 1 System parameters

| variable       | value |
|----------------|-------|
| line to line voltage $V_{L-L}$ | 650 V |
| DC link capacitor $C_{dc}$      | 800 μF |
| LC filter parameters           | $R_f = 0.7 \Omega$ $L_f = 3$ mH |
| line impedance                | $R_l = 0.38 \Omega$ $L_l = 0.15$ mH |
| VCC’s LPF time constant ($\tau$) | 0.06 s |

![Fig. 6 Root locus diagram of the proposed current loop](http://example.com/root_locus_diagram)

![Fig. 7 Simulation results of the PV system during a 3-phase to ground fault without LVRT. 3-phase Inverter Voltage, Current and DC-link Voltage](http://example.com/simulation_results)

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This paper proposes an LVRT control strategy for grid-connected PV systems. The method is based on the classic cascaded voltage and current loops in dq-frame, while the positive and negative sequences of d-component voltage are used to adjust the reference DC-link voltage to limit the inverter current during a voltage sag. The q-component current is used to supply the required reactive power to restore the voltage. The proposed method is validated in MATLAB/SIMULINK. Simulation results show that the proposed LVRT control strategy can be used for both balanced and unbalanced faults. The presented results show that for a severe voltage sag (3-phase fault), the proposed method could significantly reduce the fault current to protect the inverter from overcurrent failure. For a lighter voltage sag, for instance, the LG fault, which is the most common fault, the proposed method could limit the fault current to a reasonable level with little effect to the utility system (supplying the grid/loads with reduced active power since the voltage and current remain sinusoidal during fault). The method does not require a hard switch to switch from MPPT to a non-MPPT algorithm, which ensures a smooth transition.

5 References

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