Photovoltaic Grid Connected Inverter Crossing Control Method Based on Grid Voltage Feed forward Compensation

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Abstract. According to the requirements of relevant national standards, large photovoltaic grid connected inverters need to have zero voltage ride through (ZVRT) capability to prevent low voltage automatic disconnection, thus affecting the normal and stable operation of power system. On the basis of analyzing the ZVRT standard of PV grid connected inverter, the key technologies of inverter realizing ZVRT are discussed in detail, including grid voltage positive and negative sequence separation and phase locking, active and reactive current control of inverter, system control under unbalanced grid voltage and so on. On this basis, it is further proposed that the grid voltage feed forward component phase lead compensation link should be introduced into the system current loop, so as to improve the transient overshoot of grid connected fault. Finally, the correctness and effectiveness of the ZVRT control strategy of the PV grid connected inverter is verified by the experimental results of RTDS and a 500 kW prototype.

1. Introduction
As a typical representative of clean energy power generation, photovoltaic power generation technology of large in recent years has made considerable development and progress, especially the large scale application of photovoltaic grid connected inverter makes its influence on power grid is becoming more and more domestic and foreign scholars to study and pay attention to [1], zero voltage photovoltaic inverter through (ZVRT) technology is one of them. When the photovoltaic inverter is not high in the proportion of the power grid in low voltage system of automatic off network is acceptable, but for the power system in a large proportion of it will cause the collapse of the grid voltage and frequency to the system, has brought huge losses to the production and life. Therefore, in order to keep grid connected PV Inverter in grid voltage short time, grid connected power system must have a zero voltage operation capability [2].

Based on the analysis of the ZVRT standard photovoltaic grid connected inverter, inverter is the key technologies for the realization of the ZVRT are discussed in detail including: grid voltage positive and negative sequence and phase inverter technology, active and reactive current control technology, under the condition of unbalanced grid inverter control technology etc [3-4]. In order to compensate the inverter digital control inherent one beat delay [5], and the control loop of digital filter, grid voltage positive and negative sequence components and phase locking system caused by the
current loop voltage feed-forward phase lag, this paper further proposed in the system control loop is introduced into the grid voltage feed forward component phase lead compensator, which can effectively improve the inverter overshoot in the grid current ZVRT moment. Finally, the State Grid Electric Power Research Institute Experiment Center of the real-time digital simulator (RTDS) and a 500 kW photovoltaic grid connected inverter prototype experimental results verify the analysis and control of photovoltaic grid connected inverter ZVRT the correctness and effectiveness of the strategies discussed.

2. ZVRT control strategy and analysis of photovoltaic grid connected inverter

Fig. 1 Schematic diagram of photovoltaic grid connected inverter, wherein the supporting capacitance of DC bus $C_{dc}$; $Q_1$ to $Q_6$ inverter power tube; $i_A$, $i_B$, $i_C$ as the inductor current of three-phase grid connected filter; L three-phase AC output filter inductor; R line parasitic resistance; $C_{AC}$ side output filter capacitor; $e_A$, $e_B$, $e_C$ three-phase grid voltage.

![Figure 1 Schematic diagram of three-phase photovoltaic grid connected inverter](image)

2.1. Power grid voltage positive and negative sequence separation and phase-locked control

System grid voltage positive and negative sequence separation and phase-locked link as one of the core control technologies of PV grid connected inverter is of great significance for inverter grid connected operation. Especially the grid voltage symmetrical / appeared in response to the inverter in ZVRT asymmetric drop, achieve rapid detection of grid voltage phase tracking and the imbalance of positive and negative sequence voltage separation will be directly related to whether the grid connected photovoltaic inverter can achieve ZVRT. At present, the most commonly used three phase grid connected inverter is the positive and negative sequence separation and phase-locked scheme based on double two generalized integration (D-SOGI). [6], the positive and negative sequence separation system control block diagram is shown in Appendix A and fig. A2.

Taking the two quadrature signal $e_{\alpha}$ and $e_{\alpha}^\prime$ generated by $e_{\alpha q}^\prime$ component as an example, according to the control block diagram shown in Appendix A diagram A1, we can get the transfer function of $e_{\alpha}^\prime$ and $e_{\alpha q}^\prime$ to the input signal $e_{\alpha}$, $D(s)$and $Q(s)$and are respectively:

\[
\begin{align*}
D(s) &= \frac{e_{\alpha}^\prime(s)}{e_{\alpha}(s)} = \frac{k_s\omega_0 s}{s^2 + k_s\omega_0 ^2 + \omega_0 ^2} \\
Q(s) &= \frac{e_{\alpha q}^\prime(s)}{e_{\alpha}(s)} = \frac{k_s\omega_0}{s^2 + k_s\omega_0 s + \omega_0 ^2}
\end{align*}
\]  

(1)

In the formula, $\omega_0$ is the resonant angle frequency (that is, the power grid voltage angle velocity); $k_s$ is the damping coefficient.

The corresponding frequency curves can be obtained from the transfer function $D(s)$ and $Q(s)$, as shown in Appendix A diagram A3 (transfer function $\omega_0$ takes 314 rad / s, damping coefficient $k_s = 1$).
The transfer function of D as shown by the appendix A figure A3 (s) and Q (s) frequency curve: two generalized integral nature to achieve separation of positive and negative sequence voltage is a low-pass filter and band-pass filter respectively to filter the input voltage and frequency were obtained after filtering.

The signal, as well as the positive sequence (+ 50 Hz) and negative sequence (- 50 Hz) mixed component corresponding to the lagging 90 degree signal. So, in order to go further.

For the separation of positive and negative sequence components, four operations should be carried out according to the formula (2), and the positive sequence component $e_\alpha^+, e_\beta^+$ of the grid voltage is extracted. And the negative sequence component $e_\alpha^-, e_\beta^-$. 

\[
\begin{align*}
 e_\alpha^+ &= \frac{e_\alpha^+ - e_\beta^-}{2} \\
 e_\beta^+ &= \frac{e_\beta^+ + e_\alpha^-}{2} \\
 e_\alpha^- &= \frac{e_\alpha^- + e_\beta^+}{2} \\
 e_\beta^- &= \frac{e_\beta^- - e_\alpha^+}{2}
\end{align*}
\]  

According to the results of the separation of positive and negative sequence of grid voltage, we can further get the phase-locked loop of the grid voltage and the negative sequence phase-locked angle $\theta_g^+, \theta_g^-$ by the closed-loop phase-locked in the two-phase rotating coordinate system. The control block diagram of phase-locked system, as shown in Appendix A A4, is achieved by controlling the positive and negative sequence Q voltage components of the grid voltage, $e_q^+, e_q^-$ are zero, and realizes the positive sequence and negative sequence closed loop phase locking of the grid voltage.

2.2. Inverter active and reactive current control
Because there is no moment of inertia, when the PV grid connected inverter is ZVRT, the maximum DC bus voltage of inverter is open circuit voltage $U_{oc}$. In order to suppress the output over current during the traversing of the PV grid connected inverter, it is necessary to ensure that the inverter power module device is safe. Meanwhile, in order to ensure that the inverter does not run off the grid when the grid voltage falls, PV grid connected inverter needs to output certain reactive power to the grid according to the voltage drop of the grid, so the active and reactive current instructions of the current inner loop need to be restricted.

Considering the input of reactive power will increase the grid voltage during the period of inverter ZVRT, so as to meet the requirements of reactive power support, the formula of reactive current in Formula 1 is corrected to:

\[
I_{ord} = (0.9 - E_d^+) I_N x \
E_d^+ \leq 0.9
\]  

Type (3) with positive sequence voltage $E_d^+$ as the reactive current reference response, taking into account the effects of inverter reactive current control loop response speed, in order to meet the requirement of inverter reactive power support, the coefficient of reactive current $x$ given proper amplifier.

During the grid voltage drop, in order to restrain the output current of photovoltaic grid connected inverter and ensure the safety of power module devices, we need to limit the active current instructions of the current inner loop.
\[ I_{dref}^2 + I_{qref}^2 \leq (kI_N)^2 \] (4)

In the type: K is the maximum current rating of the power module of the inverter. The limit value of the active current of the inverter (4) and type (5) is as follows:

\[ I_{dref} \leq \sqrt{k^2 - (0.9 - E_d^r)^2} x^2 I_N \] (5)

The current loop using the traditional grid connected inverter and grid voltage feed-forward decoupling control in two-phase rotating coordinate system, the control signal through the inverse Clark transform in two-phase stationary coordinate system to generate modulation signal of \( M_\alpha \) and \( M_\beta \), finally through space vector modulation control of power tube duty ratio signal of relevant control diagram see Appendix A figure A5.

**Figure 2.** Current loop model of three-phase grid-connected inverter
3. ZVRT control strategy for PV grid connected inverter based on voltage feed-forward phase compensation of power grid

The traditional system of inverter current loop control block diagram in the discrete domain such as shown in Figure 2 (a), the \( G_i(z) \) and \( G_h(z) \) respectively for the current regulator, the zero order holder in the transfer function of the Z domain, \( i_{gref}(z) \) for a given grid current value of the Z field. As Figure 2 (a) is a discrete and continuous domain hybrid system, for the convenience of analysis, the system can be unified in the discrete domain to continuous domain, and Figure 2 (b) diagram of continuous domain control inverter current shown in the ring, in which \( G_i(s) \) and \( G_h(s) \) diagram as shown in figure 2 (a) shows, among them, \( G_i(z) \) and \( G_h(z) \) respectively for the current regulator, the zero order holder in the transfer function of the s domain, \( i_{gref}(s) \) for a given grid current value of the s field. As Figure 2 (a) is a discrete and continuous domain hybrid system, for the convenience of analysis, the system can be unified in the discrete domain to continuous domain, and Figure 2 (b) diagram of continuous domain control inverter current shown in the ring, in which \( G_i(s) \) and \( G_h(s) \) respectively. As the current regulator, the zero order holder in the transfer function of the s domain, \( T_s \) switching period (sampling period), \( i_{gref}(s) \) for a given grid current value of the s field to figure 2 (b) and the equivalent conversion available in Figure 2 (c) shown in the block diagram of control system.

4. Simulation and experimental verification

4.1. System simulation research

When the grid voltage feed forward component phase advance compensation, control strategy of photovoltaic grid connected inverter used as shown in Figure 3, when the grid voltage into the symmetric ZVRT moment, system simulation waveform of inverter as shown in Figure 3 (a) (b) as shown in Figure 3 (a), which gives the voltage feed forward component phase lead compensation before and after \( (E_d^+ \text{ and } e_{\text{lead}^+}) \) simulation waveform. The simulation waveform shows that after introducing the grid voltage feed-forward component phase advance compensation link, the dynamic response of the feed forward component of the grid voltage is improved, thus reducing the control burden of the current loop feedback loop at the instant of grid voltage drop. Figure 3 (b) for inverter three-phase current and voltage waveform simulation, the simulation results show that with the introduction of grid voltage feed forward component phase lead compensation, the grid voltage drop moment, three-phase current overshoot is well controlled, the current peak is suppressed to about 1700 A, and ZVRT during reactive power the rated current value is given.

In Figure 3 (c), the three-phase grid connected current and the power grid voltage simulation waveform of the inverter when the grid voltage is asymmetrical ZVRT are further given.

(a) Voltage feed forward component of power grid before and after the introduction of phase excess compensation
Figure 3. System simulation waveform of ZVRT after compensating phase forward component phase forward compensation of power grid voltage

5. Conclusion
The control strategy of the improved grid connected inverter system effectively suppressed the instantaneous rush current of ZVRT, and at the same time met the relevant standards and power quality requirements during the fault ride through. The simulation and experimental results fully demonstrate the correctness and effectiveness of the proposed ZVRT control strategy for PV grid connected inverter.

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