Photovoltaic Single-Phase Grid-Connected Inverter Based on Voltage and Reactive Power Support

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Abstract. In this paper, a kind of PV grid-connected inverter suitable for low voltage ride through is proposed. In order to alleviate the voltage drop at the power grid access point during the fault, the photovoltaic inverter needs to provide a certain amount of reactive power support to the power grid. The orthogonal quantities in the time domain are transformed into direct quantities by the dq rotating orthogonal coordinate system, so that decoupling control of active power and reactive power can be achieved. In order to achieve the smooth switching of the working mode, the parameter design of the PID controller needs to be analyzed according to the controlled object model. The simulation results show that the photovoltaic grid-connected inverter under the decoupling control can realize the reactive power support to the voltage drop at the grid-connected point in time.

1. Introduction

In recent years, the increase of the high-power impact load continuously threatens the stability of the grid voltage. The latest "Photovoltaic Power Station Access Power System Technical Regulations": Large and medium-sized grid-connected PV systems must have a certain low voltage ride through to ensure that the equipment can operate safely and stably for a period of time after the grid falls [1].

When voltage instability occurs at the PV inverter interconnection point, the grid-connected system needs to provide a certain amount of inductive or capacitive reactive power to prevent the collapse of the local grid voltage[2]. Since reactive power can not be transmitted over long distances, a static reactive power compensation device (SVC) is often used to make up for the reactive power shortage [3]. However, these devices undoubtedly increase the system's cost and complexity. In this paper, the energy transfer of photovoltaic system under normal conditions and the reactive power regulation of grid-connected inverter under fault condition are realized by vector decomposition of rotating coordinate system.

2. Reactive power compensation

GB/29321-2012"Photovoltaic Plant Reactive Power Compensation Technical Specification" stipulates that the photovoltaic power station should make full use of grid-connected inverter reactive power capacity and its regulatory capacity to configure adequate dynamic reactive power compensation capacity. So as to ensure the photovoltaic inverter in the specified node voltage range safe and reliable, continuous and stable operation.

According to the domestic industry on the specific requirements of reactive power voltage support, single-phase grid inverter reactive power compensation is usually determined by the grid voltage drop depth [4]. As shown in Figure 1.
In this current working state, the controller uses the sensor to collect and process the voltage of the grid connection point in real time. When the busbar access point voltage is in the range of \(0.98U_N \sim 1.02U_N\), dead zone, the PV inverter works in constant power factor control mode without reactive power compensation. When busbar access point voltage is \(0.95U_N \sim 0.98U_N\) or when \(1.02U_N \sim 1.05U_N\), calculated as follows:

\[
Q = \begin{cases} 
Q_{\text{max}} & (u \leq 0.95U_N) \\
Q_{\text{max}} + \frac{\partial Q}{\partial U} (u - U_{\text{ref} \text{(low)}}) & (0.95U_N < u < 0.98U_N) \\
0 & (0.98U_N < u < 1.02U_N) \\
-Q_{\text{max}} - \frac{\partial Q}{\partial U} (u - U_{\text{ref} \text{(high)}}) & (1.02U_N < u < 1.05U_N) \\
-Q_{\text{max}} & (u \geq 1.05U_N)
\end{cases}
\]

3. Photovoltaic Grid System

3.1 Design of Photovoltaic Grid Connection Inverter

The system equivalent model of the single-phase grid-connected inverter is shown in the figure 2[7]. The DC voltage is modulated by a full-bridge circuit into a set of unequal-width pulse signals \(U_H\). After the reactor filters out some of the high-frequency harmonics, it is connected to the power grid through an isolated step-up transformer. Where \(L\) includes the inductance value of the filter inductance and the leakage inductance of the isolation transformer. \(R\) is determined by the inductor internal resistance, the transformer copper loss, and the line impedance loss.

\[
U_{dc} + \quad + \quad L \quad R \quad i_L \quad U_H \quad \rightarrow \quad i_L \quad U_a \quad \rightarrow \quad U_{ac}
\]

Figure 2. Single-phase grid-connected inverter system equivalent model

In the above system equivalent model, the time-domain equation of the loop current in the stationary coordinate system is listed according to Kirchhoff’s voltage theorem as follows:

\[
V_H = Ri_L + L \frac{di_L}{dt} + V_a
\]

Where \(V_H\) is the single-phase full bridge output voltage, \(i_L\) is the inductor loop current, and \(V_a\) is the equivalent grid voltage coupled to the primary side of the isolation transformer. For computational convenience, these variables are transformed from a stationary two-phase orthogonal coordinate system \(a\beta\) to a rotating orthogonal coordinate system \(dq\) using a Park transformation matrix. The
principle of transformation is to produce the same total combined current [8]. As shown in the following figure 2.

![Figure 3](image)

**Figure 3.** rotating coordinate system of the voltage and current vector diagram

The voltage and current vectors in the $dq$ coordinate system are plotted in Figure 3. The vector components of each voltage and current in the rotating coordinate system can be obtained by decomposing the vectors along the coordinate system rotated by the angular frequency $\omega$ of the industrial frequency. Calculated as follows:

\[
V_H = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} [V_{H(d)}]
\]

\[
i_L = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} [i_{L(d)}]
\]

\[
V_q = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} [V_{q(d)}]
\]

Where $V_{H(d)}$ is the component of $V_H$ on the $d$ axis and $V_{H(q)}$ is the component of $V_H$ on the $q$-axis. $i_{L(d)}$ is the component of $i_L$ on the $d$ axis, and $i_{L(q)}$ is the component of $i_L$ on the $q$-axis. $V_{a(d)}$ is the component of $V_a$ on the $d$-axis. Considering that the direction of $V_a$ vector is consistent with the $d$-axis, its component on the $q$-axis is zero.

The above formula (3) (4) (5) into the formula (2), available:

\[
V_H(d) = Ri_{L(d)} + L \frac{di_{L(d)}}{dt} - \omega Li_{L(q)} + V_{a(d)}
\]

\[
V_H(q) = Ri_{L(q)} + L \frac{di_{L(q)}}{dt} + \omega Li_{L(d)}
\]

When the circuit is in constant power mode, by adjusting the single-phase full-bridge voltage component $V_{H(q)}$, you can change the size of the equivalent inductor current $i_{L(q)}$ in the same direction with the grid current to control the PV inverter on the ac side Transmission of active voltage of grid voltage. When the circuit is in constant reactive power mode, by adjusting the inverter bridge voltage component $V_{H(d)}$, you can change the size of the equivalent inductor current $i_{L(d)}$ component perpendicular to the direction of the grid voltage to control the photovoltaic inverter absorption or send reactive power.

### 3.2 PID control in a rotating coordinate system

The above equation (7) (8) is normalized. The vector equation of the controlled object in the rotating two-phase orthogonal coordinate system is as follows:

\[
\vec{V}_{H(q)} = (R + j\omega L)\vec{I}_{L(q)} + \vec{V}_{a(q)}
\]

By deducting (9) above, the transfer function of PV inverter in the frequency domain is as follows:

\[
G_{H(i)} = \frac{\vec{V}_{H(\omega)} - \vec{V}_{a(\omega)}}{\vec{I}_{L(\omega)}} = \frac{1}{R + j\omega L}
\]
PWM pulse width modulator can be seen as a high-gain proportion of links. Often the delay in software operation leads to a delay in its response [9]. The delay time $T_{PWM}$ is related to the switching period, which is typically on the order of 0.01ms. The transfer function of the PWM pulse width modulator is as follows:

$$G_{PWM} = \frac{K_{PWM}}{1 + \tau_{PWM}s}$$  \hspace{1cm} (9)

$K_{PWM}$ is the amplification factor of PWM pulse width modulator in the formula (11), $K_{PWM} = 220$ in this example. $T_{PWM}$ is the delay time of the PWM pulse width modulator. Since the switching frequency is 20kHz in this project, $T_{PWM} = 5 \times 10^{-5}$. Photovoltaic single-phase grid inverter closed-loop control diagram is shown in the Figure 4:

![Figure 4. Photovoltaic single-phase inverter with closed-loop control block diagram](image)

As can be seen from Figure 5 above, the open-loop transfer function of the control loop is:

$$G_{op} = G_{control}(s)G_{PWM}(s)G_{R}(s)$$

$$= G_{control}(s) \frac{K_{PWM}}{1 + \frac{1}{R} + \tau_{PWM} + \frac{1}{L/R}s}$$  \hspace{1cm} (10)

When designing a closed-loop controller, the dynamic performance of the system should be improved as much as possible to reduce the overshoot and adjustment time during the follow-up process. Typical Type I systems operating in underdamped conditions greatly reduce the risk of single-phase inverter currents exceeding allowable values during dynamic response, ensuring safe and reliable operation of the device [10]. The transfer function of the current controller is as follows:

$$G_{control}(s) = K_p + \frac{K_i}{\tau} = \frac{K_p(\tau s + 1)}{\tau s}$$

Where $\tau = \frac{K_p}{K_i}$, $K_p$ is a proportional constant, $K_i$ is an integral constant. Use the $(\tau s + 1)$ in the regulator to eliminate the inertial component $[1 + (L/R)s]$ of the larger time constant in the controlled object. The corrected open-loop transfer function of the system is as follows [11]:

$$G_{op} = \frac{K_p(\tau s + 1)}{\tau s} \frac{K_{PWM}}{1 + \frac{1}{R} + \frac{1}{L/R}s}$$

$$= \frac{K}{s(1 + \tau s)}$$  \hspace{1cm} (12)

Where $T = T_{PWM}$, $K = (K_t K_{PWM})/R$, $\tau = K_p/K_i = L/R$. The logarithmic frequency characteristics of the open loop transfer function is shown in the Figure 5:
In the log amplitude frequency characteristic, the intersection of the curve and the horizontal axis is the cutoff frequency. For a typical I-type system, the greater the cut-off frequency, the better the dynamic performance, but the smaller the phase margin is, the poorer the stability of the system. According to the system dynamic performance index, using Siemens "best tuning" method. The parameters are as follows:

\[ \xi = 0.707, \quad KT = 0.5 \]  \hspace{1cm} (13)

From the above formula (14) (15), calculated:

\[ K_p = 0.036, \quad K_i = 2.27 \]  \hspace{1cm} (14)

4. **Simulation analysis**

In this paper, according to the principle of photovoltaic single-phase grid, it is proposed to design a 6kw inverter to convert 380V DC bus voltage into 220V AC power. In order to optimize the power distribution for optimal purposes, a more flexible inverter grid control strategy is obtained. Specific design indicators are shown in the Table 1:

**Table 1.** Photovoltaic grid inverter design parameters

| Parameter                  | Specification |
|----------------------------|---------------|
| Input voltage              | 380V±10V      |
| Output voltage             | 220V          |
| Output voltage ripple      | <3%           |
| Maximum output power       | 6kw           |
| Switching frequency        | 20kHz         |

Using Matlab / Simulink to build single phase inverter simulation model [12]. As shown in FIG. 6, the measurement module collects the instantaneous value of the grid voltage and current in real time, and the phase angle of the grid voltage is calculated by the PLL (Phase Locked Loop). The feedback signal is compared with the given target current value after passing through the dq coordinate transformation matrix. The PI controller is used to realize the zero-static error correction of the controlled object. Finally, the anti-dq coordinate transformation matrix is used to obtain the PWM pulse-width modulated fundamental signal.
Figure 6. Photovoltaic grid-connected inverter simulation model

In Figure 6, the use of universal bridge module to achieve full-bridge main circuit functions. The simulation time is 0.1s. By adjusting the values of the $i_a$ and $i_d$ step signal modules, the effective values of the active and reactive power current components are changed. Scope oscilloscope output waveform as shown in Figure 8 below, the horizontal axis is the time axis, the blue waveform represents the grid voltage, the red waveform represents the filter inductor current. The target value of the active current component is 36A. The simulation result on the oscilloscope shows that the effective value of the inductor current is 35.4A.

Figure 7. (A) Inductance current and grid voltage waveform in constant power mode
(B) Inductance current and grid voltage waveform in constant reactive power mode

As can be seen from the simulation results in FIG. 7A, the filter inductor current and the grid voltage are in the same direction to achieve constant power mode operation. From FIG. 7B, it can be seen that the current phase of the filter inductor leads the grid voltage by 90 degrees, and the PV inverter operates at constant in reactive power mode.
In the simulation, the jump time of the step signal generator module is used to simulate the controller response when the grid fault occurs. The switching time is 0.05s. It can be seen from the simulation results of the oscilloscope in Figure 8 that the fundamental current value of the filter inductor can reach the steady state value in time and the working state of the photovoltaic inverter is switched from the constant power mode to the constant reactive power mode. $K_p$, $K_i$ parameter design rationality.

5. Conclusion
In the field of photovoltaic in new energy sources, this paper draws the following conclusions for photovoltaic grid-connected inverters: (1) The single-phase grid-connected photovoltaic inverter based on reactive voltage support can realize the low voltage crossing of grid-connected equipment and can alleviate the voltage drop at the grid-connected point under the fault condition. (2) The PI control in the rotating coordinate system can realize the decoupling control of grid-connected power quickly and stably. The simulation model built by Matlab / Simulink proves that the system has good dynamic and static performance.

References
[1] ZHANG Haiyu, LIU Chuang, CHAO Qin, et al. Research on relay protection issues of grid-connected photovoltaic system with LVRT ability[J]. Power System Protection and Control, 2015, 43(3): 53-60.
[2] K. &C. Mamandur, R. D. Chenoweth. Optimal Control of Reactive Power Flow for Improvements in Voltage Profiles and for Real Power Loss Minimization[J], IEEE Trans On PAS, 1981, 100(7): 3185~3194.
[3] Harmonics Characteristic Parameter, Methods of Study ,Estimates of Existing Values in Network ,WG 36-O,Electra No.77,1982.
[4] Antonios Marinopoulos, Fabio Papandrea, Muhamad Reza, et al. Grid Integration Aspects of Large Solar PV Installation: LVRT Capability and Reactive Power/ Voltage Support [A],IEEE Trondheim Power Tech [c]. 2011:1-8
[5] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, “A review of single-phase grid-connected inverters for photovoltaic modules,” IEEE Trans. Ind. Appl., vol. 41, no. 5, pp. 1292–1306, Sep./Oct. 2005.
[6] J. P. Benner and L. Kazmerski, “Photovoltaics gaining greater visibility,” IEEE Spectr., vol. 29, no. 9, pp. 34–42, Sep. 1999.
[7] ZHANG Chenghui, YE Ying, CHEN Allan, et al. Research on grid-connected photovoltaic inverter based on output current control [J]. Transactions of China Electrotechnical Society, 2007, 22(8): 41-45.
[8] ROWE C N, SUMMERS T J, BETZ R E, et al. Implementing the virtual output impedance concept in a three phase system utilising cascaded pi controllers in the dq rotating reference
frame for microgrid inverter control[C]//15th European Conference on Power Electronics and Applications(EPE). Lille, France, 2013: 1~10.

[9] A. Capel, J. Jalade, J. C. Marpinard, and M. Valentin, “Large signal dynamic stability analysis of synchronized current controlled modulators. Application to sine-wave high power inverters,” in 1982 IEEE PESC Rec., pp. 101–109.

[10] Zames, G. Feedback and optimal sensitivity: model reference transformations, multiplicative seminorms and approximate Inverse. IEEE Trans. Automat. Contr. 1981, V01. AC-26: 301-320

[11] M. N. El-Gamal and G. W. Roberts, “Very high-frequency log-domain bandpass filters,” IEEE Trans. On Circuits and Systems II, vol. 45, no. 9, pp. 1188-1198, Sept. 1998.

[12] Henriksson D, Cervin A, Aren K E. TrueTime: Real-time control system simulation with Matlab/Simulink [A].Proceedings of the Nordi Matlab conference [C]. Copenhagen Denmark, 2003.