Research On VSG Comprehensive Control Strategy For Power Grid Voltage Sag

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Abstract. Virtual Synchronous Generator (VSG) photovoltaic inverter still has the problems of surge current and voltage overcharge when the grid voltage drops. Aiming at the problems mentioned above, the comprehensive control strategy for AC/DC is proposed. The direct current (DC) side adopts the strategy of super-capacitor energy storing and switching Maximum Power Point Tracking (MPPT) derating, the alternating current (AC) side adopts the control strategy of virtual impedance and the vector difference of limited voltage, which are based on the quasi-proportional resonance. Particle swarm optimization (PSO) is used to optimize its parameters because of the difficulties in adjusting parameters of quasi-proportional resonance control by experience. This strategy can track on the voltage with no difference when the voltage is normal, it can also limit the overcharging voltage and the surge current into the demanded range when the voltage drops. Finally, the effectiveness of the strategy proposed in the paper is verified by simulation.

1. Introduction
In recent years, with the increasing popularity rate of new energy generation, it has occupied a relative large proportion in the grid capacity[1]. The accompanying question is how to solve the stability problem brought to the grid, and it has become an important topic. Therefore, the VSG technology is proposed[2].

However, traditional virtual synchronous generators still have the problems of impact current or voltage overcharge, which may exceed the tolerating capacity of power electronic components and result in the damage of them[3]. There are two traditional low-voltage ride-through strategies for photovoltaic virtual synchronous generators. The first method is improving on the basic of virtual synchronous generator control strategy. The second method is switching the virtual synchronous generator control strategy to the low voltage ride through (LVRT) strategy when the grid voltage drops. When the DC side is photovoltaic, the grid voltage will drop severely if the photovoltaic power is not controlled, not only the surge current problem will occur, but also the excess energy on the DC side cannot be absorbed, which may result in the over-voltage of the DC bus.

Therefore, in this paper, the author considers to combine the improved topology structure with the MPPT derating strategy, and add energy storing devices to the photovoltaic DC side. During the drop of the grid voltage, the energy storing devices absorb surplus energy generated by photovoltaic and adjust the maximum power algorithm to reduce the photovoltaic output power.
At present, commonly used control methods in VSG current control are: proportional resonance (PR), PI, hysteresis and model predictive control. By contrast, PR control has advantages of simple and easy to achieve, fast response speed and reducing harmonic waves effectively. So, it has attracted more and more attention from scholars. In order to solve the problems above, this paper proposes the comprehensive control strategy on AC/DC side.

2. basic principle of the virtual synchronous inverter

The voltage source virtual synchronous generator system selected in the paper is shown in figure 1. It mainly includes two parts: ontological mathematical model which simulates the synchronous generator (SG) and the control part which simulates the external characteristics of the SG[5].

In Figure 1, $L_s$, $R_s$, $C_s$ are the inductance, resistance and capacitance of the LCL filtering, the synchronous impedance of the synchronous generator; voltage $e_a$, $e_b$, $e_c$ are the inner electrical potential of the synchronous generator; $C_{dc}$ is the capacitance of the DC bus; $v_{gabc}$, $i_{gabc}$ are grid voltage and current; $U_{dc}$ is the DC bus voltage. $\omega^*$ is the reference angular frequency, which is obtained by frequency detection; $P^*$, $Q^*$ are the reference active power and reactive power which are outputted from the ontological model; $e$, $\theta$ are the output signal of the output section[6].

At present, the ontological mathematical model of the virtual synchronous generator is mainly the second-order mathematical model of the synchronous generator, which mainly includes the electromagnetic and mechanical parts of SG[7]. The virtual synchronous generator control part equation is shown in equation (1):

$$
\begin{align*}
(P^* - P) / \omega^* + D_p (\omega^* - \omega) &= J \frac{d\omega}{dt} \\
Q^* + D_q (V^* - V) - Q &= K \frac{de}{dt}
\end{align*}
$$

3. PSO algorithm optimizing quasi-PR control current loop

The control current loop structure studied in this paper adopts the traditional current control loop structure[8], it is shown in Figure 2. Select the $Ed$ direction as the d-axis direction; $E_d$ and $E_q$ are d-axis components and q-axis components of e; $i_{gd}$, $i_{qs}$, $V_{gd}$, $V_{qs}$ are d-axis components and q-axis components of the grid current and voltage. $i_d^*$ and $i_q^*$ are reference values of the grid current; $V_d$ and $V_q$ are d-axis and q-axis components of the inverter output inner electric potential; $R_1 + \omega L_1$ is the AC switching virtual impedance when the grid voltage drops[9].
Figure 2. Principle of current loop based on PR control

The lower detection link is used to detect the grid voltage and current the grid. S1 is the virtual impedance switching switch described later[10]. The switch S1 turns on when the detection link detects a drop in the grid voltage. Considering the demand of virtual synchronous inverter for current dynamic response, the paper uses the quasi-proportional resonant controller to replace the current control loop's traditional PI controller, its expression is shown in equation (2):

\[
\begin{align*}
V_d &= V_{gd} + \Delta V_d - \omega L_{g} i_{gd} \\
V_q &= V_{qg} + \Delta V_q - \omega L_{q} i_{qg} \\
\Delta V_d &= QPR(i_{gd}, i_{d}^*) \\
\Delta V_q &= QPR(i_{qg}, i_{q}^*)
\end{align*}
\]

In equation (3), \(\Delta V_d, \Delta V_q\) are output value of the VSG current control loop; \(L=2L_s\) is the equivalent inductance of the filter. The transfer function of the quasi-PR controller is shown in equation (3):

\[
G(s) = K_p + \frac{2K_i \xi \omega_0 s}{s^2 + 2 \xi \omega_0 s + \omega_0^2}
\]

In equation (3), \(K_p\) is the coefficient of proportionality; \(\xi\) is the damped coefficient; \(K_r\) is the resonance coefficient; \(\omega_0\) is the fundamental frequency. Its amplitude-frequency characteristic is obtained from the transfer function. Compared with PR control, the quasi-PR improves the gain and bandwidth of the fundamental frequency.

Therefore, the paper adopts PSO particle swarm algorithm to optimize the parameters. The specific optimizing process of time multiplied by absolute error integral (ITAE) is shown in Figure 3. In Figure 3, \(K_{p1}\) is the \(K_p\) of PR controller; \(K_i\) is the integral parameter of PI controller.

4. AC/DC comprehensive control strategy

4.1. The comprehensive strategy analysis of AC side based on virtual impedance and limiting voltage vector difference current-limiting.
Through synchronous generator grid-connected model, the VSG grid-connected model is simply equivalent to Figure 4. When there is a three phase short-circuit in synchronous generator model grid, the switch S is turned on to represent it.[10]

When the grid voltage drops, the fault current expression (4) at present obtained from Figure 5 is:

$$i = \frac{e - v}{R + jX}$$  \hspace{1cm} (4)

In equation (5), $e$ is the inner electric potential of VSG; $v$ is the voltage vector; $v_s$ is the grid voltage; $i$ is the fault current; $R + jX$ is the equivalent reactance from VSG to Point of Common Coupling (PCC), the LCL filter impedance of VSG is usually small. Through analyzing (10), we can know that the surge current is proportional to the difference between the output inner electric potential of the virtual synchronous generator and the PCC voltage vector, and is inversely proportional to the impedance from virtual synchronous generator to the fault point.

(1) The method of reducing the voltage vector difference between the inner electric potential and the fault point. Its 4 limit values can be obtained through analysis and calculation, which are shown in equation (5), and corresponding amplitude limiting links are added in the current loop.

$$
\begin{align*}
\delta e_{d,\text{max}} &= (V_d^* - V_{d,\text{gi}}) \leq \delta e_1 \\
\delta e_{d,\text{min}} &= (V_d^* - V_{d,\text{gi}}) \geq \delta e_2 \\
\delta e_{q,\text{max}} &= (V_q^* - V_{q,\text{gi}}) \leq \delta e_3 \\
\delta e_{q,\text{min}} &= (V_q^* - V_{q,\text{gi}}) \geq \delta e_4
\end{align*}
$$  \hspace{1cm} (5)

(2) The method of increasing the virtual impedance. Calculate the increased virtual impedance $R_1 + \omega L_1$, when the grid voltage drops, the equation (6) can be expressed as:

$$i = \frac{\delta e}{(R + jX) + (R_1 + j\omega X)}$$  \hspace{1cm} (6)

Analyze the equation (6), we can know that when we adopt the above method, we must increase the impedance value to limit the current in the allowable range if voltage drops a lot. But it will change the total impedance of virtual synchronous generator grid-connected system, which can affect the impedance characteristic of the system.[11] Therefore, the paper adopt the method of switching virtual impedance. The virtual impedance is not turned on when the grid voltage is normal, it is turned on when the detection link detects a voltage drop, this method can solve the above problem. The AC comprehensive control strategy adopted in this paper is shown in Figure 5, and the table of switch strategy is shown in Table 1.

| Grid status  | Sp   | Sq   | S1                      |
|--------------|------|------|-------------------------|
| normal       | Connect the upper contact | Connect the lower contact |                         |
| Voltage sag  | Connect the lower contact | Connect the upper contact |                         |

In Table 1, Sp and Sq are DC side MPPT derating switches, S1 is the AC side switch of vector difference between virtual impedance and the limiting voltage.
4.2. The DC-side MPPT derating control strategy and the comprehensive control strategy based on super electric capacity energy storing.

In this paper, the author considers to combine the improved topological structure with the MPPT derating strategy, and add energy storing devices to the photovoltaic DC-side. During the drop of the grid voltage, the energy storing devices store surplus energy and adjust the maximum power algorithm to reduce the photovoltaic output power. The energy storing devices send energy back to the grid when the grid voltage is restored.

Therefore, the DC-side adopts the comprehensive control strategy based on the combination of super electric capacity energy storing and MPPT derating algorithm. The super electric capacity adopts the bidirectional DC converter topological control, the specific control strategy is shown in Figure 6.

In Figure 6, $g_1$ and $g_2$ are IGBT tubes; $L$ is energy storing inductance; $C$ is super electric capacity; $U_{dc}^*$ is the reference value of DC bus voltage; $U_{dc}$ is the measured value of the DC bus voltage; $i_{dc}$ is the inductance current. Whether DC converter is in BUCK ($i_{dc}>0$) mode or BOOST ($i_{dc}<0$) mode is judged according to the direction of $i_{dc}$, further decide to charge or discharge for the super electric capacity. Its specific converter control method can be seen in literature[12].

5. Verification and analysis of the simulation
MATLAB/simulink is used to simulating verify the comprehensive control strategy proposed in this paper. The relevant simulation parameters are as follows: photovoltaic rated power 21 MW; grid frequency 50 Hz; voltage amplitude 3 kV. By calculating, the LCL filter parameters are selected as: $L_s 0.4$ mH, $C_s 8$ mH, $R_s 10$ Ω.

| Table 2. THD content table |
|---------------------------|
| Current controller | THD |
| Tradition PI | 3.7 % |
| QPR | 1.8 % |
The simulating verification includes three parts: 1. The harmonic wave inhibiting effect of the strategy. 2. The inhibiting effect of the surge current. 3. The inhibiting effect of the DC-side voltage overcharging.

Table 2 shows the THD content comparison of the control method adopted in this paper and traditional control methods. The quasi-PR controller can inhibit surge current rapidly and reduce the harmonic wave content at the same time.

As shown in figure 7, the three-phase grid voltage drops to about 20% at $t = 1.1$ s and recovers at 1.22s.

![Figure 7. Voltage waveform Diagram of power grid](image)

When the grid voltage drops, the output current of traditional VSG inverter is shown in Figure 8.

As shown in Figure 8b, the moment the grid-connected point voltage drops to 20%, the inverter will output (about 4 pu) surge current because the output electric potential of traditional virtual synchronous inverter cannot change suddenly. The surge current amplitude will be larger if the voltage drops more deeply. As shown in Figure 8a, a period of time after the fault recovers at 1.22s, the current recovers to normal after a transient process (inertia time) of 0.4s.

![Figure 8a. Current waveform of traditional VSG in fault](image)  
![Figure 8b. Current Amplitude in Traditional VSG in fault](image)

Under the same simulation condition (grid voltage drops to 0.2 pu), after adopting the AC-side virtual synchronous generator’s surge current inhibiting strategy based on vector difference between virtual impedance and limiting voltage, the current wave forms of virtual synchronous inverter in fault stage, the current dynamic characteristics at inhibiting moment and in fault process are respectively shown in Figure 9~11. Figure 9 shows that the surge current can be limited to different values by adjusting the limiting voltage vector difference and virtual impedance value.

![Figure 9. Current Amplitude with Value](image)

As shown in Figure 10, during the fault period from 1.1~1.22s, the inverter output surge current is basically limited to about 1.1 pu which is far less than the surge current without adopting this strategy. 10ms after voltage drops, the inverter output current is limited to the required value, the response time is within 10 ms (within two vertical dashed lines), which proves that this inhibiting strategy has good dynamic characteristics. As shown in Figure 11. After the grid voltage restored, there’s no current distortion and the transition is smooth (within two vertical dashed lines) by using this strategy, which proves that this inhibiting surge current strategy is feasible.
Figure 10. Voltage sag instantaneous current waveform.

Figure 11. Current waveform during voltage recovery.

Figure 12 shows the DC-side bus voltage using super electric capacity to store energy without adopting derating strategy. The voltage was overcharged to 1.3 pu from 1.11s to 1.22s. The voltage overcharging will be more severe if the grid voltage drops more deeply. Figure 13 shows the DC-side voltage optimized by PSO adopting this comprehensive strategy. The voltage peak appears at 1.12s, but dynamic process is short and the amplitude is relatively small. There’s almost no overcharge from 1.12~1.22s, and the voltage is limited to the range about 1 pu.

The above simulation analysis shows that the comprehensive control strategy studied in this paper is fast, correct and effective.

6. conclusion

Aiming at the problem of surge current and voltage overcharging of the traditional photovoltaic VSG when the grid voltage drops, the paper proposed the AC/DC-side comprehensive control strategy and made the simulation analyzing verification, the conclusions are as follows:

The AC-side comprehensive control strategy proposed in this paper can inhibit the surge current and reduce the harmonic wave content rapidly and effectively in principle; the DC-side comprehensive control strategy can also inhibit the voltage within the specified range effectively.

The paper does not make the stability analysis of the system. In the follow-up work, we plan to analyze its stability and its switching moment. All in all, this strategy can achieve rapid and effective inhibition to the surge current and DC voltage overcharging.

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