Research on frequency modulation control of photovoltaic power generation system based on VSG

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Abstract
In order to improve the friendliness of the grid connection of new energy power generation, the new energy photovoltaic (PV) unit is equivalent to a synchronous generator in the power system and a virtual synchronous generator (VSG)-controlled PV energy storage complementary grid-connected power generation system model is established and studied to analyze the VSG. When power is supplied to the load together with the power grid, the energy storage unit inside the VSG will release and store the electrical energy according to the fluctuation of the PV output, which plays the role of the adjustment of the prime mover; in the case of load power fluctuations, and power grid assume the corresponding active power regulation according to their capacity. The amount of active power adjustment to jointly and maintain the power balance inside the system under the condition of fluctuating load power. The overall system architecture and control strategy of PV grid-connected inverter based on VSG algorithm are proposed. The PV-VSG proposed here not only takes into account the maximum power point tracking control but also has independent participation in the power supply. A series of characteristics of synchronous generators, such as network frequency modulation voltage regulation and inertia damping, can effectively improve the new energy PV power generation system and promote the new energy consumption. The results of system simulation and field demonstration operation fully show the effectiveness and correctness of the proposed control strategy based on VSG algorithm.

Keywords: photovoltaic power generation; VSG; frequency modulation; grid connection control

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1. INTRODUCTION
At present, most of the traditional new energy generation is connected to the grid through the inverter of advanced power electronic converter. With the advantages of flexible control, weak coupling with power grid, wide range of application and high efficiency and energy saving, the power electronic converter has rapidly replaced the synchronous machine power generation system based on electromechanical energy conversion, large inertia delay and difficult control, and it has become the main form of new energy power generation [1]. However, in the new background of the rapid improvement of the penetration of power electronic interface, the access of large-scale traditional new energy generation has brought a huge challenge to the operation control and security and stability of the power grid [2,3].

Synchronous generator has the advantage of being natural and friendly to power grid. If the control of power electronic system is flexible, the grid-connected inverter has the external characteristics of synchronous generator, it will be able to realize the friendly access of new energy power generation system with power electronic grid connected device and improve the stability of power system [3]. Based on this idea, domestic and foreign scholars put forward virtual synchronous generator (VSG) control technology of power electronic grid connected device.

In the traditional power generation system, the synchronous generator is driven by external energy to provide power to the power grid. It has inertia and damping characteristics, can follow the fluctuation of output power to participate in the voltage-frequency regulation of the power grid and has excellent grid-connected performance [4]. If we refer to the actual power system
operating experience and the control performance of the synchronous generator, it is possible to achieve the goal of smooth access to the inverter grid, which is very helpful to the many problems and challenges faced by the current distributed power grid connection [5,6]. This leads to VSG technology. The VSG technology is to use the second-order electromechanical model of the synchronous generator to refer to the mechanical equations and electromagnetic equations of the synchronous generator to regulate the output of the grid-connected inverter, so that the distributed power generation grid-connected system is in operation and regulation. The performance is similar to that of a synchronous generator [7–9].

At present, VSG has been widely concerned by scholars at home and abroad in the field of distributed generation and Microgrid; but in these fields, VSG input DC side power supply mainly uses energy storage battery [10,11]. For new energy photovoltaic (PV) power generation, the output of PV power supply is easily affected by external environmental factors, with strong randomness and volatility. Therefore, the traditional VSG is difficult to be applied to the field of new energy PV power generation from either the system topology or the control strategy itself.

Taking the new energy PV power generation as the research object, this paper proposes the overall system architecture and control strategy of PV grid connected inverter based on VSG algorithm [12]. The proposed system overall control scheme not only keeps the traditional PV grid-connected inverter to realize the control of PV maximum power point tracking (MPPT) but also has a series of external characteristics of synchronous generators such as self-response grid frequency modulation/voltage regulation, inertia damping, etc., so as to effectively improve the integrity of new energy PV power generation system. The results of system simulation and field demonstration operation fully show the effectiveness and correctness of the proposed control strategy based on VSG algorithm.

2. PV-VSG SYSTEM ARCHITECTURE

When frequency events (especially low-frequency events) occur in the power grid, conventional synchronous generators respond to the frequency fluctuations of the power grid by releasing the mechanical kinetic energy stored in the rotor. In the same way, PV-VSG also needs to provide additional active power to respond to grid frequency changes and participate in the primary frequency modulation of the system [13]. In general, the output control of PV cells follows the MPPT control principle to achieve the maximum power utilization of PV cells. Therefore, PV panels can no longer provide additional active power in grid frequency events, so a certain capacity of energy storage and corresponding energy conversion device should be configured in the PV-VSG system architecture to realize the PV-VSG’s self-frequency modulation in response to grid frequency fluctuations [14].

The topological structure of PV-VSG system is shown in Figure 1. Its main circuit is composed of DC/AC part composed of three-phase inverter full-bridge circuit and DC/DC part composed of two-way buck boost circuit [15]. Among them, the energy storage battery as the input of DC/DC part, its output and PV battery are connected to DC bus and input as DC/AC part and, finally, through the three-phase inverter full-bridge circuit unified inverter grid connection.

3. CONTROL STRATEGY OF PV-VSG SYSTEM

3.1. PV-VSG DC/AC partial control

The DC energy generated by the traditional distributed power supply is input as the interface inverter after the boosting step, and the AC power is output through the current conversion function of the power electronic device in the interface inverter and then is integrated into the power grid through the function of the filter element such as the inductance [16,17]. The controller collects the current and voltage signals on the grid side and the AC side of the inverter and performs the adjustment calculation to obtain the inverter’s grid-connected voltage quality command value, so that the distributed power system's electrical energy can follow the grid standard. When the installed capacity of the distributed power generation system is large, it can be directly integrated into the power grid through the converter, omitting the DC boost link and reducing the loss of output in the components [18]. The energy characteristics of the distributed power supply determine that its output cannot be directly connected to the large power grid. This requires the control of the converter of the grid-connected interface to achieve a safe and stable grid-connected output. Existing control methods mostly follow the regulation principle of traditional generators to make the output of the interface inverter track the power quality of the power grid.

From the point of view that the main circuit of the DC/AC part of PV-VSG is equivalent to the electrical part of the synchronous generator, it can be considered that the fundamental wave of the neutral point voltage of the three-phase bridge arm of the inverter $u_{abc}$ simulates the internal potential of the synchronous generator, the inductance of the inverter side $L_f$ simulates the synchronous reactance of the synchronous generator and the output voltage (capacitance voltage) of the inverter $e_{oabc}$ simulates the synchronous generation. The terminal voltage and the output inductance current of the generator simulate the output current of the synchronous generator.

In order to realize the primary frequency regulation function (frequency active power droop function) of the generator set, the prime mover in the generator set is equipped with a governor. The function of the governor is as follows: when the grid frequency is different from the rated frequency, the governor will automatically change the opening of the prime mover valve, thus changing the mechanical power output by the prime mover. The relationship between the mechanical power output by the prime mover and the grid voltage angle frequency is as follows:

$$P_m = P_{ref} + D_p(\omega_n - \omega_g).$$  (1)
where motion equation of synchronous generator rotor is as follows:

\[ G_J \omega = J \frac{d\omega}{dt} + D \omega \]

which is usually obtained by the PV MTTP control algorithm, and \( J \) is the moment of inertia of synchronous generator and \( D \) is the droop coefficient of frequency active power.

At this time, the PV cell is the main input power of PV-VSG; therefore, \( P_{ref} \) in formula (1) can be regarded as the output power of PV cell. Thus, there are:

\[ P_{ref} = \left( U_{dc} - U_{qref} \right) G_{dc}(s), \tag{2} \]

where \( U_{qref} \) is the PV DC bus voltage reference instruction, which is usually obtained by the PV MTTP control algorithm, and \( G_{dc}(s) \) is the DC bus voltage regulator.

Considering the influence of damping winding, the mechanical motion equation of synchronous generator rotor is as follows:

\[ P_m - K_d (\omega - \omega_g) - P_e = J \omega d\omega/dt, \tag{3} \]

where \( P_e \) is the electromagnetic power of synchronous generator, \( J \) is the moment of inertia of synchronous generator and \( K_d \) is the mechanical damping coefficient.

Simultaneous (1)–(3), it can be concluded that the DC/AC partial active loop equation of PV-VSG considering the effect of governor is

\[ \left( U_{dc} - U_{qref} \right) G_{dc}(s) + D_p (\omega_n - \omega_g) - K_d (\omega - \omega_g) - P_e \approx J \omega d\omega/dt \tag{4} \]

It can be seen from equation (4) that the DC/AC partial active loop of PV-VSG well simulates the inertia, damping and primary frequency modulation characteristics of synchronous generator.

The output voltage of synchronous generator will decrease with the increase of output current. Therefore, it is necessary to add excitation controller to adjust the excitation current of synchronous generator in real time, so as to adjust the amplitude of internal potential and maintain the constant output voltage of synchronous generator. The closed-loop control equation of excitation controller is as follows:

\[ i_f = G_e(s) \left( U_{ref} - U_o \right), \tag{5} \]

where \( U_{ref} \) is the reference voltage amplitude, \( U_o \) is the synchronous generator output voltage amplitude and \( G_e(s) \) is the regulator transfer function of the excitation controller.

In order to ensure that the output voltage can track the reference voltage without static difference, \( G_e(s) \) must contain an integral link, which can choose an integral regulator or PI regulator.

In order to realize the primary voltage regulation function (voltage reactive power droop function) of PV-VSG, the amplitude of its reference voltage will change with the change of its output reactive power, and the change rule is as follows:

\[ U_{ref} = U_n + (Q_{ref} - Q_e) / D_q, \tag{6} \]

where \( U_n \) is the rated voltage amplitude; \( Q_{ref} \) is the reactive power given (corresponding to the rated voltage \( U_q \)), which is usually given by the scheduling of the previous layer; \( Q_e \) is the actual output reactive power of PV-VSG; and \( D_q \) is the voltage reactive power droop coefficient.

The closed-loop control equation of the excitation controller considering the effect of primary voltage regulation can be obtained by combining (5) and (6):

\[ i_f = G_e(s) \left[ D_q (U_n - U_o) + (Q_{ref} - Q_e) \right] / D_q. \tag{7} \]

When \( G_e(s) \) is the integral regulator, order \( G_e(s) / D_q = 1/(K_e) \), formula (7) can be rewritten as

\[ i_f = \left[ D_q (U_n - U_o) + (Q_{ref} - Q_e) \right] / (K_e). \tag{8} \]

Equation (8) describes the closed-loop control equation of DC/AC partial excitation controller of PV-VSG. Since the excitation regulator indirectly controls the reactive power output
of the synchronous generator by controlling the voltage change at the end of the generator, for the inverter controlled by the high-frequency power electronic switch, the modulation wave and the output voltage of the bridge arm (equivalent terminal voltage of the synchronous generator) in the low frequency can be regarded as the proportional relationship. Therefore, the output of type (8) excitation regulator can be directly the amplitude of PV-VSG modulation wave voltage. Formula (8) can be rewritten as

$$E_m = \left[D_q \left(U_n - U_o\right) + \left(Q_{ref} - Q_d\right)\right] / (K_d). \quad (9)$$

It can be seen from equation (9) that the reactive loop of DC/AC part of PV-VSG simulates the primary voltage regulation characteristics of synchronous generator.

PV-VSG active loop and reactive loop respectively simulate inertia damping and automatic frequency and voltage regulation characteristics of synchronous generator. Among them, the output of the reactive loop is the frequency and phase of the voltage command of the bridge arm of the inverter, and the output of the reactive loop is the amplitude of the voltage of the bridge arm of the inverter, then the expressions of the three-phase modulation waves $e_{ma}$, $e_{mb}$ and $e_{mc}$ are respectively

$$\begin{align*}
e_{ma} &= E_m \sin \theta \\
e_{mb} &= E_m \sin (\theta - 2\pi/3) \\
e_{mc} &= E_m \sin (\theta + 2\pi/3)
\end{align*} \quad (10)$$

The virtual impedance is introduced to obtain the reference of PV-VSG’s DC/AC partial current inner loop command in three-phase static coordinate system:

$$i_{Lrefabc} = \left(e_{mabc} - e_{gabc}\right) / (sL_W + r_W), \quad (11)$$

where $L_W$ and $r_W$ are the virtual impedance inductance and its parasitic resistance, respectively, and $e_{gabc}$ is the three-phase grid voltage.

The obtained current inner loop command reference and the three-phase inductance current feedback signal $i_{Labc}$ obtained by sampling are coordinate-transformed, and the current inner loop controller is constructed under the two-phase rotating coordinate system to realize the closed-loop control of the inverter output inductance current. The current inner loop control equation is as follows:

$$\begin{align*}
M_{Ud} &= \left(i_{dref} - i_Ld\right) \left(K_p + K_i/s\right) - \omega L_f i_{Ld} + E_{gd} \\
M_{Uq} &= \left(i_{qref} - i_Lq\right) \left(K_p + K_i/s\right) - \omega L_f i_{Lq} + E_{gq}
\end{align*} \quad (12)$$

where $i_{dref}, i_{Ld}, E_{gd}$ are the reference signal of inductive current, the feedback signal of three-phase inductive current and the components of $d, q$ axis of grid voltage in two-phase rotating coordinate system, respectively; and $K_p, K_i$ are the proportion coefficient and integration coefficient of current inner loop regulator, respectively.

The output signal 1,1 of current inner loop in $d, q$ coordinate system is transformed by anti-Park transformation, and then the modulation signals $M_{Ua}, K_{Uβ}$ in two-phase static coordinate system are obtained. Finally, the duty cycle signal of DC/AC part of PV-VSG is generated by space vector modulation.

3.2. DC/DC partial control of PV-VSG

As mentioned above, PV-VSG is required to independently increase or absorb certain active power to provide active positive or negative support to the grid in case of system frequency events such as low frequency or high frequency, thus contributing to grid frequency recovery. In order to realize this function, energy storage and corresponding bidirectional DC/DC converter are configured in PV-VSG system.

In case of low-frequency events in the power grid, the energy storage configured by PV-VSG will transfer energy to DC bus through bidirectional DC/DC converter according to the frequency drop of the power grid, and finally convert it into active power through DC/AC part of PV-VSG, provide active support to the power grid and participate in the primary regulation of the power grid frequency. Similarly, when high-frequency events occur in the power grid, energy storage and its bidirectional DC/DC converter reduce the total output of PV-VSG by absorbing the active power from the DC bus.

When PV-VSG responds to the frequency change of power grid, the inertia and primary frequency modulation power generated by PV-VSG are all borne by the energy storage and DC/DC part. Therefore, the reference command of DC/DC part power can be obtained as follows:

$$P_{dref} = D_p (\omega_n - \omega_g) - K_d (\omega - \omega_g). \quad (13)$$

The integrated formulas (4) and (9)–(13) gives the overall control block diagram of PV-VSG system as shown in Figure 2.

4. SIMULATION AND EXPERIMENTAL VERIFICATION

4.1. Simulation analysis

In order to verify the feasibility and correctness of the proposed PV-VSG system control strategy and grid connection implementation scheme, a 500-kW PV-VSG system model is built in MATLAB, in which the main circuit parameters and control parameters of the system are as follows: the rated power of PV is $P_{PV} = 500kW$, the voltage of energy storage battery is $U_{in}$ out of 200~480 V, the DC/DC inductance is $L_{in} = 0.8mH$, the filter inductance is $L_f = 0.15mH$, the filter capacitance is $C_f = 600μF$, $D_p = 16000$, $D_q = 20000$, the mechanical damping coefficient is $K_d = 8000$, the virtual moment of inertia is $J = 0.33kg\cdot m^2$, the primary voltage regulation coefficient is $K = 318$, the switching frequency of DC/AC is 3.2 kHz and the switching frequency of DC/DC is 6.4 kHz. It should be pointed out that
considering the actual development cost of PV-VSG device, the configured energy storage capacity is designed according to the rated output power of PV $10\% \times 15\text{s}$, and the response frequency fluctuation range of grid is $(50 \pm 0.5)\text{Hz}$ and the super capacitor is selected as the energy storage body.

In order to verify the self-frequency modulation function of PV-VSG in response to grid frequency fluctuation, Figure 3a and b show the simulation waveforms of PV-VSG system when the grid frequency steps from 50 to 49.5 and 50.5 Hz respectively. In Figure 3a and b, $P_{e\text{dc}}$ is the output power of energy storage and DC/DC bidirectional converter, $\omega$ is the angular frequency of DC/AC part of PV-VSG and $U_{\text{dcbus}}$ is the DC bus voltage of PV-VSG.

The simulation waveform shows that in the initial stage, PV-VSG follows the maximum power tracking control according to the current lighting conditions and the output power of PV-VSG is about 350 kW. When the power grid frequency suddenly changes from 50 to 49.5/50.5 Hz in 2s, PV-VSG can respond to the power grid frequency mutation autonomously. The energy stored in PV-VSG can output/absorb energy to DC bus through bidirectional DC/DC converter, and finally participate in the primary frequency modulation of power grid through PV-VSG inverter. The simulation waveform shows that under the designed control parameters, the maximum power of energy storage participating in grid frequency modulation is about 50 kW. In addition, since the PV-VSG active loop simulates the inertia and damping characteristics in the rotor motion equation of synchronous generator, the output angular frequency of PV-VSG does not change dramatically with the sudden change of grid frequency at the moment of grid frequency mutation. At the same time, the voltage...
of PV-VSG DC bus keeps good stable control during the whole frequency event.

In order to verify the independent voltage regulation function of PV-VSG in response to grid amplitude fluctuation, Figure 4a and b shows the simulation waveform of PV-VSG system when the grid voltage amplitude changes from 1 pu step to 1.05/0.95 pu. $Q_e$ is the output reactive power of PV-VSG, and $E_m$ is the fundamental amplitude of the output voltage of the bridge arm of PV-VSG inverter.

The simulation waveform shows that when the power grid voltage suddenly changes from 1 to 1.05/0.95 pu in 2s, within the rated capacity of PV-VSG, PV-VSG can provide reactive power support to the power grid and automatically participate in the primary voltage regulation of the power grid. Under the current designed control parameters, the reactive power provided by PV-VSG to the power grid is about ±200 kvar. At the same time, in the whole process of voltage event, the voltage of PV-VSG DC bus keeps good stable control.

Considering that the output of PV panels is always changing under the influence of light intensity, in order to verify the overall control stability of PV-VSG when the illumination changes, Figure 5 shows the simulation waveform of PV-VSG system when the light intensity of PV panel changes from 350 to 450 kW (when the light changes, the frequency/amplitude of power grid keeps the rated value, that is, PV-VSG does not participate in the primary frequency modulation/voltage regulation of power grid).

The simulation waveform shows that MPPT can be realized rapidly by PV-VSG DC bus voltage when the illumination changes suddenly in 2s, so as to maintain the maximum power output of PV-VSG. In addition, due to the effect of virtual inertia and damping in PV-VSG active loop, the output angular frequency of PV-VSG does not change dramatically with the sudden change of illumination (similar to the sudden change of given mechanical power of prime mover), so as to effectively reduce the impact of PV-VSG instantaneous output on power grid Power impact, improve PV-VSG and netizen’s good character.

4.2. Experimental verification

In order to further verify the correctness and effectiveness of the proposed PV-VSG control strategy, a 500-kW PV-VSG was developed and tested in a national wind and solar energy storage and transmission base. The main circuit and control parameters of the experimental system are consistent with those of the simulation model. Figure 6 shows the waveform of PV-VSG participating in the primary frequency modulation experiment recording when the frequency of analog grid $f_g$ is lower than the rated frequency.
The recording data shows that when the frequency of the simulated power grid drops from 50 to 49.5 Hz, the energy storage battery and bidirectional DC/DC converter configured by PV-VSG rapidly increase the additional active power to respond to the frequency change of the power grid. In this process, PV-VSG well realizes the stable control of DC bus voltage and the output power PV of PV cells does not change greatly (the light intensity does not change significantly at the moment of frequency fluctuation). Finally, $P_e$ increased from 450 to 500 kW during the power grid frequency drop and the support time was about 15 s, which realized active participation in the primary frequency regulation of power grid.

5. CONCLUSION

This paper proposes the overall system architecture and control strategy of PV grid connected inverter based on the algorithm of VSG, which combines the PV grid connected inverter with the control technology of VSM. On the basis of ensuring the control operation of PV MPPT, the PV grid-connected inverter can actively participate in grid frequency modulation/voltage regulation and other functions. The test results of system simulation and field demonstration operation fully verify the correctness and effectiveness of the proposed control strategy. The proposed PV virtual synchronous generator technology effectively improves the PV power generation and netizens’ friendliness. In the future research, we can further discuss the optimal design of control parameters of PV virtual synchronous generator, and the impact analysis of large-scale PV virtual synchronous generator on grid stability after connecting to the grid.

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