Postprint: Control of Grid-Connected Photovoltaic Systems Based on Virtual Synchronous Machines

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Abstract

Since photovoltaic renewable energy sources are predominantly integrated into the power grid via power electronic interfaces, power systems originally dominated by synchronous generators have been transformed into high-frequency power-electronic-based systems. To address the issue of reduced rotational inertia in power systems caused by large-scale photovoltaic integration, this study investigates a bipolar three-phase grid-connected system, employs a virtual synchronous generator (VSG) control strategy, and performs simulation verification in Matlab/Simulink. The simulation results demonstrate that the photovoltaic grid-connected system utilizing VSG control can emulate the inertia and frequency regulation characteristics of conventional synchronous generators.

Full Text

Research on Grid-Connected Photovoltaic System Control Based on Virtual Synchronous Generator

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Abstract

As photovoltaic (PV) energy increasingly integrates into power grids through power electronic interfaces, traditional power systems dominated by synchronous generators are transforming into high-frequency power-electronic-based systems. This paper addresses the problem of reduced rotational inertia in power systems caused by large-scale PV integration. Using a bipolar three-phase grid-connected system as the research object, a virtual synchronous generator (VSG) control strategy is proposed and validated through Matlab/Simulink simulations. The results demonstrate that the PV grid-connected system employing VSG control can effectively emulate the inertia and frequency regulation characteristics of conventional synchronous generators.

Keywords: Grid-connected photovoltaic, virtual synchronous generator, inertia, frequency modulation

1 Introduction

Conventional power systems remain dominated by synchronous generators on the generation side, which provide power stability and facilitate grid integration of clean energy sources such as PV. However, the increasing penetration of PV energy through power electronic interfaces reduces the overall rotational inertia of the power system, posing challenges to grid stability. To address the limitations of traditional grid-connection methods, this paper proposes a VSG control strategy for PV grid-connected systems.

Three common PV grid-connection control methods exist: (1) Constant Voltage/Constant Frequency (V/f) control, which regulates inverter output voltage and frequency based on reference values and is primarily used in islanded operation; (2) Constant Power (PQ) control, which injects power according to specified active and reactive power references but lacks voltage and frequency regulation capability; and (3) Droop control, which adjusts output frequency and voltage through active and reactive power modulation, thereby providing primary frequency and voltage regulation characteristics similar to synchronous generators, but without inherent rotational inertia and damping properties. These limitations restrict the grid’ s ability to accommodate PV energy resources.

The fundamental concept of the Virtual Synchronous Generator (VSG) involves introducing energy storage systems to distributed generation units and implementing appropriate control strategies that incorporate virtual rotational quantities, enabling distributed power sources to exhibit synchronous generator characteristics during grid transients. By adopting VSG control, PV systems can deliver smooth power to the grid, reduce the impact of renewable energy integration, and appear as equivalent synchronous generators from the grid perspective, possessing frequency regulation capability and adjusting output power according to load fluctuations.

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2 PV Virtual Synchronous Generator System Structure

The VSG hardware architecture comprises a main circuit and a control circuit, as illustrated in [Figure 1: see original paper]. This study focuses on a VSG design based on a DC-side PV-storage energy system, with a grid-connected inverter facilitating power conversion from DC to AC. The topology consists of both main and control circuits, where the inverter is powered by a PV source, voltage is stabilized by an energy storage battery, and the inverter circuit employs a three-phase full-bridge configuration.

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3 Virtual Synchronous Generator Control Strategy Analysis

The VSG model can be established through mechanical and voltage equations. The core equations are:

$$J\frac{d\omega}{dt} = T_M - T_E = \Delta T = T_M - T_E - D(\omega - \omega_g)$$

$$(P_T - P_E) = D_p(\omega_N - \omega)$$

$$(Q - Q_N) = D_q(u_N - u)$$

where α is the mechanical angular acceleration; J is the moment of inertia; Ω is the rotor mechanical angular velocity; T_M and T_E are mechanical and electromagnetic torques, respectively, corresponding to P_T and P_E as mechanical and electromagnetic power; ΔT is the unbalanced torque acting on the rotor shaft; ω, ω_g, and ω_N are the actual electrical angular velocity, grid electrical angular velocity, and rated electrical angular velocity, respectively; P_N, Q_N, P, and Q are the rated active power, rated reactive power, input active power, and output reactive power, respectively; and D_p and D_q are the P-f and Q-u droop coefficients.

In the VSG control strategy, P and P_T share the same physical meaning, i.e., $P = P_T$. Under conditions of small grid frequency deviation, we can approximate $\omega_g \approx \omega_N$. Combining the equations yields:

$$\frac{d(\omega_N)}{dt} = (P_N - P_E) - D_p(\omega_N - \omega)$$

where $D_p' = (D_p + D_\omega)/\omega$.

Differentiating both sides of the equation gives:

$$\frac{d^2(\omega_N)}{dt^2} = (P_N - P_E) - D_p(\omega_N - \omega)\frac{dt}{dt} + \omega_N$$

From this derivation, the VSG P-f control loop is obtained, with its control block diagram shown in [Figure 2: see original paper]. The output voltage phase angle θ is generated for voltage vector synthesis and inner-loop coordinate transformation.

The VSG schematic diagram based on these equations is presented in [Figure 3: see original paper], where Q_{VSG} represents the reactive power output from the VSG. Under grid-connected conditions, the grid provides voltage support. Setting $Q_N = 0$ enables the system to operate at unity power factor, allowing the PV source to deliver maximum active power to the grid.

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4 System Simulation Analysis

A simulation model was built in Matlab/Simulink to validate the proposed design. The main simulation parameters are listed in .

** Simulation System Parameters**

Parameter	Value
Rated active power (kW)	MATH_{VALUE}1
Rated reactive power (var)	MATH_{VALUE}2
DC voltage (V)	MATH_{VALUE}3
Rated voltage (V)	MATH_{VALUE}4
Rated frequency (Hz)	MATH_{VALUE}5
Switching frequency (Hz)	MATH_{VALUE}6
Filter inductance and capacitance (mH, F)	MATH_{VALUE}7
Grid inductance (mH)	MATH_{VALUE}8
Generator regulation coefficient	MATH_{VALUE}9

where ϕ is the generator regulation coefficient, $\phi = 1/2\pi D_p$.

The system initially operates in islanded mode with a 20 kW load. To verify the VSG dynamic performance, the following load changes are applied: a 10 kW load increase at 0.6 s, a 20 kW load decrease at 1.0 s, and a 20 kW load increase at 1.4 s. The VSG output voltage and current waveforms are shown in [Figure 4: see original paper]. The output voltage remains constant, while the current responds rapidly to load changes.

The system frequency waveform is presented in [Figure 5: see original paper]. When the load increases by 10 kW, the system frequency changes by 0.2 Hz, consistent with the generator regulation coefficient setting and Equation (3). The frequency variation exhibits inertia due to the moment of inertia J. The VSG output active power waveform, shown in [Figure 6: see original paper], matches the calculated results from Equation (2).

For grid connection analysis, the system operates with a 3 kW load in islanded mode. The grid switch is closed at 2.4 s. At the moment of grid connection, the grid output current waveform shows distortion, as depicted in [Figure 7: see original paper]. The total harmonic distortion (THD) is 2.16%, as shown in [Figure 8: see original paper], which meets national grid connection requirements. After grid connection, active power is shared between the grid and VSG, with a total output power of 3 kW, as illustrated in [Figure 9: see original paper].

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5 Conclusion

To address the limitations of conventional grid-connection methods, this paper adopts a VSG-based grid-connection control strategy and validates the approach through simulation analysis. Beginning with the mathematical model of synchronous generators and combining it with generator droop equations, a VSG model is established. The implementation process of the VSG control strategy is thoroughly analyzed, and simulation experiments are conducted in Matlab/Simulink. The experimental results demonstrate that PV systems employing VSG control can actively participate in grid frequency regulation, exhibiting VSG external characteristics such as frequency modulation and large inertia. This approach holds practical significance for future power systems with increasing renewable energy penetration.

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