Regulation Performance of Virtual Synchronous Generator Applied in Renewable Energy System

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Abstract. The conventional synchronous generator (SG) can regulate the active and reactive power for frequency and voltage stability, when the system fluctuates. In renewable energy generation system (RES), the stability problem of RES can be solved by adding virtual inertia and damping in the control strategy of the grid-connected inverter. The grid-connected inverter and renewable energy system with this kind of control strategy, called as virtual synchronous generator (VSG), acts as a synchronous generator. In this paper, the topology of grid-connected PV array and energy storage system is proposed. The VSG used in grid-connected inverter, is modelled as stator and rotor model by stator voltage equation and rotor motion equation, respectively. Meanwhile, the VSG control mechanism, based on droop control and model of VSG, can be divided as active power–frequency and reactive power–voltage control. Besides, the system stability is analyzed based on small signal model, for the design of inertia and damping. The simulation model is designed by MATLAB/Simulink for the implementation of VSG. In simulation, it is compared that the dynamic regulation performance of VSG with different control coefficient, such as virtual inertia, virtual damping, droop coefficient and integral coefficient. The optimization for regulation performance in simulation provides an appropriate selection method of the control coefficient for VSG.

1. Introduction
Recently, with the rapid development of renewable energy system (RES), the stability problem of voltage, frequency and power angle of the power system are becoming serious [1, 2]. In conventional power system, the synchronous generator (SG) can regulate the active power to adjust the system frequency by its governor. Meanwhile, its excitation regulator takes an important role in adjusting the system voltage by regulating the reactive power. During sudden fluctuation of power or voltage in the grid, the SGs is able to supply or absorb power to suppress frequency and power oscillation, thanks to its mechanical inerance and the damping caused by the mechanical friction. In the renewable energy system, the power electronic converters are utilized as the interface between renewable sources and grid. However, the power converters like inverters do not have the properties of inertia or damping, which affects the power stability [3].
It has been proposed in [4] that a robust droop controller for accurate proportional load sharing among inverters operated in parallel. The control strategy is robust against numerical errors, disturbances, noises, feeder impedance, parameter drifts and component mismatches. However, this droop control can only regulate the power distribution, but can not supply or absorb power when system oscillation.

To add inertia and damping properties into the control of inverters, a concept of virtual synchronous generator (VSG) was proposed firstly in 2007, by the University of Leuven for simulating the external characteristics of SG [5, 6]. This kind of control strategy was applied in power electronic converters [7,8]. In the scheme of VSG, the inverter of RES utilizes the control strategy, which can simulate the frequency modulation and voltage regulation characteristics of SG, due to the virtual inertia and damping properties [9].

In this paper, a virtual synchronous generator is utilized in grid-connected PV array and energy storage system. The topology can be divided as renewable sources and grid-connected inverter. RES and its DC/DC converter are described briefly. Grid-connected inverter is controlled by VSG, which is modelled as stator and rotor model. The control strategy of VSG can be divided as active power–frequency control and reactive power–voltage control. The active power–frequency control involves the droop control and rotor motion equation, which can simulate the frequency regulation characteristics of SG. The reactive–voltage control is based on the stator model of VSG, which simulates the voltage regulation characteristics of SG. As a final task, it optimizes the dynamic regulation performance by an appropriate selection of the control coefficient for a case of study. Organization of the paper is as follows. Section 2 reviews the structure, model and control strategy of the VSG. Section 3 introduces the simulation topology and parameters, analyses the dynamic regulation performance of the VSG, and evaluates the influence of the control coefficient. Section 4 concludes the paper.

2. The Principle of the VSG

2.1. Topology
The VSG applied in RES is shown in Figure 1, where the RES involves the wind turbine, PV array and storage system. Wind turbine is connected by rectifier with motor control, whilst PV array and storage system are connected by DC/DC converter. The RES and its converters are paralleled with the DC bus, which can be seen as prime motor of the conventional power system. The grid-connected inverter with the virtual synchronous control plays the role of the conventional SG [10]. The frequency regulation for wind power generation is realized by the release of kinetic energy from the fan impeller. Different from the wind power, the damping and inertia for frequency regulation in PV array is provided by the paralleled energy storage system [11].

Figure 1. Topology of virtual synchronous control applied in renewable energy sources.
2.2. Renewable Energy System

The RES involves the wind turbine, PV array and storage system. In this paper, the grid-connected PV array and energy storage system is utilized, where PV array is the power source. Meanwhile, DC bus voltage is controlled by energy storage system, which also provides the virtual inertia and damping for PV array.

In Figure 2, the PV array is connected to DC bus by Boost converter. In Figure 3, controlling the Boost converter by disturbance observation method, the Maximum Power Point Tracking (MPPT) of the PV array can be realized.

The hybrid energy storage system applied in RES shown in Figure 4, is composed of super-capacitor and battery. The virtual inertia in the VSG control strategy and the adjustment of the DC voltage is realized through the charging and discharging of the energy storage system. Therefore, the super-capacitor and battery are connected respectively to DC bus by the bidirectional buck-boost converter (BBC), which can operate in buck or boost mode. The battery or super-capacitor is charged when the BBC operates in buck mode, but is discharged when the BBC operates in boost mode.

Figure 2. VSG control applied in grid-connected PV array and energy storage system.

Figure 3. PV system and its MPPT control.
According to Figure 4, the double closed loop with lowpass filter is utilized. The outer loop is used to regulate the DC bus voltage, while the inner loop can regulate the battery or super-capacitor current. Comparing the DC bus voltage $V_{dc}$ with the voltage reference $V_{dc\text{ref}}$, the voltage deviation is obtained and used as the input of PI regulator. Then the current reference $I_{ref}$ is obtained. For the battery, the current reference $I_{b\text{ref}}$ is the low-frequency component separated from $I_{ref}$. The battery current deviation is obtained by comparing $I_{b\text{ref}}$ with the actual battery current $I_b$, and used for the PI regulator and PWM generation.

The lead-acid or lithium battery is an energy-type energy storage device, and can be used to compensate the low-frequency power deviation with its large capacity. The super-capacitor is a power-type energy storage device, can be used to compensate the high-frequency power deviation with its fast power response. The energy management system of RES can make full use of the complementary characteristics of the battery and super-capacitor, compensate the power fluctuation, and improve the overall reliability of the hybrid energy storage system.

2.3. Modeling of VSG

2.3.1. Rotor Model of VSG. The modeling of the mechanical part of VSG is based on the motion equation of rotor. The rotor motion equation of SG is\[^{[12,13]}\]

$$\begin{align*}
J \frac{d\omega}{dt} &= T_m - T_e - D(\omega - \omega_0) \\
\frac{d\theta}{dt} &= \omega - \omega_b
\end{align*}$$

(1)

where $T_m$ and $T_e$ are the mechanical and electromagnetic torque of VSG, respectively. $\omega$, $\omega_0$ are the instantaneous grid angular velocity and the synchronous angular velocity, respectively. $J$ and $D$ are the virtual inertia and damping, respectively. $\theta$ is the rotor position angle\[^{[14]}\].

To simplify the system, the rotor pole pairs $p$ is set as 1, so that the electrical angular velocity $\omega$ equals to mechanical angular velocity $\omega_m$. Neglecting the influence of velocity change on damper winding, $\omega_m$ equals to synchronous angular velocity $\omega_0$. Since the VSG operates around $\omega_0$, the relationship between torque and power can be shown as

$$\begin{align*}
T_m &= \frac{P_m}{\omega_m} = \frac{P_m}{\omega_0} \\
T_e &= \frac{P_e}{\omega} = \frac{P_e}{\omega_0}
\end{align*}$$

(2)
where $P_m, P_e$ are the mechanical and electromagnetic power of VSG, equal to the input and output power of grid-connected inverter, respectively\[11\].

2.3.2. Stator Model of VSG. The modeling of the electromagnetic part of VSG is based on the electrical equation of stator. The steady-state equation is

$$E = U + I(R_s + jX_s)$$

where $E, I, U$ represent the stator electromotive force, stator current and terminal voltage, respectively. $X_s, R_s$ are the filter reactance and parasitic resistance of filter reactance, which can be seen as the synchronous reactance and resistance of SG, respectively.

2.4. Control Strategy

2.4.1. Active Power–frequency Control. It is shown in Figure 5 that the droop characteristic curve between active power and frequency of conventional SG. While the system loads increase or decrease, the SG regulates the active power to adjust the system frequency by its governor, so that the system can be stable\[15\].

The droop control equation between active power and frequency of SG is

$$P_{ref} - P = -K_f(f_{ref} - f)$$

Figure 5. Droop characteristic between active power and frequency of SG.

To simulate the droop control of SG, the virtual mechanical power $P_m$, power reference $P_{ref}$, system frequency $f$ and frequency reference $f_{ref}$ in VSG can be set as:

$$P_m = P_{ref} + K_f(f_{ref} - f)$$

where $K_f$ is the droop coefficient of active power-frequency curve, $f_{ref}$ is the reference frequency of power system.

Combining equation (1) and (5), the active power-frequency control scheme can be depicted in Figure 6.

Figure 6. Active power-frequency control scheme of VSG.
2.4.2. Reactive Power–voltage Control. SG can also regulate the reactive power to adjust the system voltage by its excitation regulator. It can be depicted in Figure 7 that the droop characteristic curve between reactive power $Q$ and voltage $U$ of SG.

![Figure 7. Droop characteristic between reactive power and voltage of SG.](image)

The change of reactive power caused by droop control $\Delta Q_u$ is

$$\Delta Q_u = K_u (U_{ref} - U)$$

where $K_u$ is the droop coefficient of reactive power-voltage curve, $U_{ref}$ is the reference voltage of power system. So, the total reactive power change is $\Delta Q = Q_{ref} - Q + \Delta Q_u$.

The voltage deviation caused by the $\Delta Q$ can be obtained by integrating $\Delta Q$. And the amplitude of reference phase voltage $E_m$ can be obtained by

$$E_m = U_{ref} + \frac{1}{K} \int (Q_{ref} - Q + K_u (U_{ref} - U)) dt$$

where $K$ is the integral coefficient.

![Figure 8. Reactive power-voltage control scheme of VSG.](image)

The overall control scheme is depicted in Figure 9. The reference phase of $\theta$, reference voltage amplitude $E_m$ can be obtained by $P-f$ control, $Q-U$ control, respectively. Then, the reference voltage $U_r$ can be used to generate PWM signals by PWM generator.

![Figure 9. The overall control scheme of VSG](image)
2.5. Stability Analysis and Parameter Selection

According to previous analysis, small signal stability will be analyzed to promote the regulation performance of the proposed VSG, and provide the guidance for parameter design.

The electromagnetic power of VSG $P_e$, can be denoted as

$$ P_e = \frac{EU}{X_s} \sin \theta \quad (8) $$

Combing equation (1), (2) and (8), it can be obtained that

$$ J \omega \frac{d^2 \theta}{dt^2} = P_m - \frac{EU}{X_s} \omega \sin \theta - D \frac{d \theta}{dt} = P_m - \frac{EU}{X_s} \omega \theta - D \omega \frac{d \theta}{dt} \quad (9) $$

Small signal model can analyze the system stability with the input power fluctuation or system disturbance. For small change in the virtual mechanical power $P_m$, the transfer function for the change of rotor position angle $\theta$ to change of $P_m$ can be designed as$^{[16]}$

$$ \frac{\dot{\theta}(s)}{P_m(s)} = \frac{1}{J \omega^2 + D \omega s + \frac{EU}{X_s} \omega} \quad (10) $$

The pole of the transfer function are

$$ s_{1,2} = \frac{-D \pm \sqrt{D^2 - 4J \frac{EU}{\omega X_s}}}{2J} \quad (11) $$

It can be concluded that the poles are in left half of s-plane, so the system is stable. Besides, the system can operate in critical damping state with the critical inertia $J_0$

$$ J_0 = \frac{\frac{D^2 \omega X_s}{4EU}}{\omega X_s} \quad (12) $$

For operating in stable state, the VSG should be under damping system, so the inertia $J$ should be larger than the critical inertia $J_0$.

3. Simulation and Discussion

To verify the validation of VSG control strategy applied in grid-connected PV array and energy storage system, the simulation model is designed based on MATLAB/Simulink. The structure and parameters of simulation are shown in Figure 2 and Table 1, respectively.

Table 1. Parameters for VSG.

| Parameter | Values |
|-----------|--------|
| Input power $P_{ref}$ | 5000W |
| Reference frequency $f_{ref}$ | 50Hz |
| Reference reactive power $Q_{ref}$ | 0 |
| AC voltage $U_{ref}$ | 380V |
| Virtual inertia $J$ | 0.02kg·m² |
| Virtual damping $D$ | 2.5 |
| VSG $P-f$ droop coefficient $K_f$ | 100 |
| $Q-U$ droop coefficient $K_U$ | 100 |
| Integral coefficient $K$ | 5000 |
| The filter inductor $L_f$ | 6.4mH |
| The parasitic resistance $R$ of filter inductor | 0.5Ω |
| The filter capacitor $C_f$ | 8μF |
| The transmission line inductor $L_s$ | 3.6mH |
| PV array Maximum power $P_m$ | 5000W |
Voltage at maximum power point(MPP) $V_m$  200V
Current at maximum power point $I_m$  25A
Energy storage system Nominal voltage $V_N$  300V
Rated capacity  96Ah

Figure 10 shows the influence on $f$ of $K_f$, $D$ and $J$ when PV power fluctuation. In simulation, during 0-0.1s, the system is in the startup process and has not yet reached the steady state. The system reaches to steady state at 0.2s. The irradiation of PV array changes from 800W/m$^2$ to 1000 W/m$^2$ at 0.3s, which lead to the input power of VSG increases from 4000W to 5000W. Comparing Figure 10(b) and Figure 10(a), the power-frequency droop coefficient $K_f$ is different while virtual damping $D$ and virtual inertia $J$ are the same. It takes 0.1s to reach the steady state when the power frequency $f$ increases at 0.3s with $K_f=100$, while takes 0.08s with $K_f=1000$. It shows that the system frequency can be regulated to steady state faster with the larger $K_f$. Comparing Figure 10(c) and Figure 10(a), it can be seen that the frequency fluctuation would be smaller with larger virtual damping $D$. The system response is quicker with the smaller $J$, comparing Figure 10(d) and Figure 10(a).

According to Figure 10s, it can be concluded that the system overshot and fluctuation of frequency would be smaller with the larger $K_f$, larger $D$ and smaller $J$. Besides, the system response of frequency is quicker with the larger $K_f$ and smaller $J$.

It is depicted in Figure 11s that the influence on $P_e$ of $K_f$, $D$ and $J$ when three-phase fault occurs. Three-phase fault occurs at 0.3s and lasts to 0.4s in Figure 11s. Similar to Figure 10s, it can be concluded that the active power fluctuation can be suppressed with large $D$, and power response is quicker with the larger $K_f$ and smaller $J$.

Figure 10. Influence on $P_e$ of $K_f$, $D$ and $J$ when PV power fluctuation.
The influence on $U$ of $K_U$ and $K$ when the reactive power reference $Q_{ref}$ changes at 0.3s is illustrated in Figure 12. $Q_{ref}$ changes from 0 to 2000 var at 0.3s, which lead to the AC voltage $U$ increase. Comparing Figure 12(b) and Figure 12(a), the reactive-voltage droop coefficient $K_U$ is different while integral coefficient $K$ is the same. The AC voltage amplitude $U_m$ changes to 314.5V with $K_U=100$, while changes to 312.3V with $K_U=1000$. It can be seen that the voltage fluctuation would be smaller with larger $Q-U$ droop coefficient $K_U$. Comparing Figure 12(c) and Figure 12(a), It takes more than 0.3s to reach the steady state when the $Q_{ref}$ changes at 0.3s with $K=5000$, while takes 0.1s with $K=1000$. It can be seen that the system response of voltage is quicker with smaller integral coefficient $K$.
The simulation results show that the renewable energy system is able to regulate the system frequency and voltage by the control of virtual synchronous generator. Besides, the dynamic regulation performance can be improved with the appropriate control coefficient selection.

4. Conclusion
It is proposed that the topology, model, and control strategy of VSG utilized in grid-connected inverter, whose input ports are the PV array and battery system. In Simulation based on MATLAB/Simulink, the dynamic regulation performance is compared with different control parameters. It can be concluded that the system response of frequency is quicker with smaller virtual inertia and larger P-f droop coefficient. The system overshot and fluctuation of frequency would be smaller with larger virtual damping and P-f droop coefficient. Besides, it can be concluded that the voltage fluctuation would be smaller with larger Q-U droop coefficient, and the response of voltage is quicker with smaller integral coefficient. The comparison of regulation performance in simulation provides optimization and appropriate parameter selection for VSG.

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