

Modeling and simulation of virtual synchronous generator applications in improving the stability of microgrids

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ABSTRACT

To address stability challenges caused by the rapid integration of inverter-based renewable energy, this paper presents an overview of Virtual Synchronous Generator (VSG) control in microgrids and develops its mathematical model. The approach is validated through a MATLAB/Simulink simulation framework. The results demonstrate that the VSG effectively provides virtual inertia, dampens frequency oscillations, and enhances grid stability under disturbances, confirming its high potential for modern, renewable-heavy power systems.

Keywords: Virtual synchronous generator; Renewable energy; Grid inertia; Microgrid; Simulation.

1. INTRODUCTION

The rapid development of renewable energy [1–3] has led to a significant decline in the number of synchronous generators in power systems. Replacing conventional generating units with inverter-based sources, such as photovoltaic power plants, reduces system inertia, resulting in faster and more difficult-to-control frequency variations. Figure 1(a) illustrates this phenomenon using the German power grid as an example, where the inertia constant (H) varies significantly with the penetration level of wind and solar power, particularly in December when wind generation reaches its peak. In addition, the inertia constant H shown in Figure 1(b) decreases to as low as 3 seconds at certain times, leading to an increase in the rate of change of frequency (ROCOF) and larger frequency oscillations. According to [4], system stability can be improved by maintaining a sufficient number of conventional synchronous generators to ensure a minimum level of inertia; however, this approach reduces operational efficiency and has negative environmental impacts.

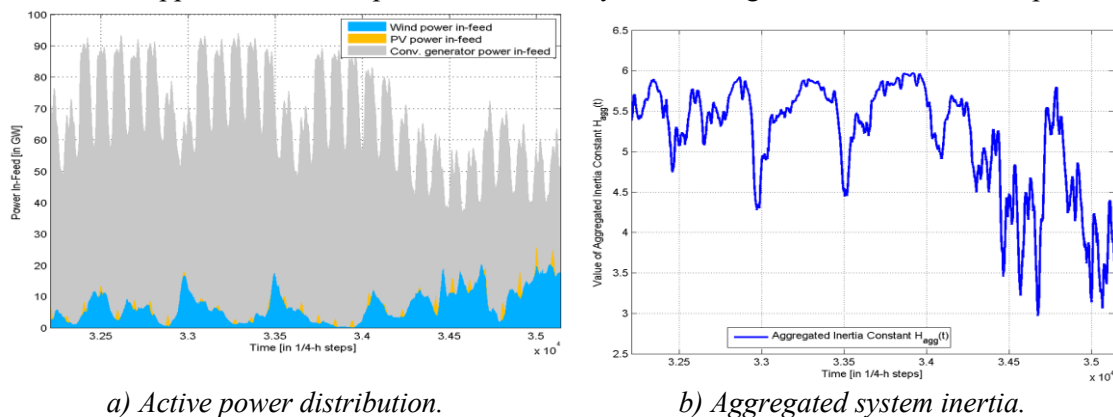
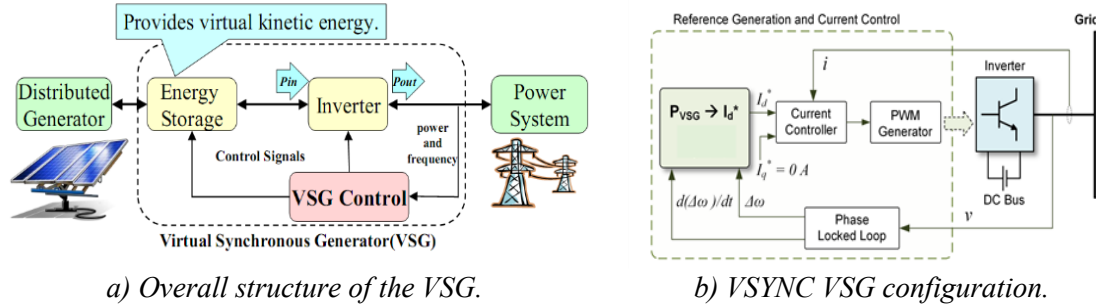


Figure 1. Overview of the German power grid in 2012 [6].

To enhance grid stability, several solutions have been proposed, each with distinct limitations: synchronous condensers provide physical inertia but incur high investment, operation and management costs [5]; renewable energy sources offer "synthetic inertia" [4, 7] but their efficiency depends heavily on operating conditions; and energy storage systems stabilize frequency [8] but

are constrained by capacity, degradation, and cost. Among these, Virtual Synchronous Generators (VSGs) have gained significant attention by emulating conventional generator characteristics through power electronics [9–11], though optimizing virtual inertia and damping coefficients remains a challenge [12, 13]. However, while most existing literature focuses on hardware, utility-scale systems, or grid-connected operations [9–13], systematic investigations into MATLAB/Simulink-based VSG frameworks for educational and rapid-validation purposes in islanded microgrids remain limited. To fill this gap, this study develops a MATLAB/Simulink-based VSG model for a microgrid and evaluates the effects of different emulated inertia constants on power sharing, frequency response, and ROCOF, providing a flexible platform for education, research, and advanced control strategy development. Therefore, this study develops a VSG simulation model for a microgrid using MATLAB/Simulink and analyzes the results under various parameter settings to evaluate its feasibility and applicability in teaching and research in the field of Control and Automation at Electric Power University. The subsequent sections present the fundamental concepts, modeling approach, simulation results, and conclusions.



a) Overall structure of the VSG.

b) VSYNC VSG configuration.

Figure 2. Structure of the virtual synchronous generator (VSG) [9, 10, 15].

2. VIRTUAL SYNCHRONOUS GENERATOR

2.1. VSG concept and structures

A VSG is a control approach for inverters that enables them to emulate the inertia characteristics and frequency regulation response of conventional synchronous generators in power systems [14]. An overview of a grid-connected VSG system is illustrated in Figure 2(a) [15]. The main components of a VSG system include an energy storage unit (Battery Energy Storage System – BESS), an inverter, and a control system.

Based on the control principle, VSGs can be classified into two main categories: swing-equation-based VSGs and frequency–power feedback-based VSGs. The “swing equation” of a conventional synchronous generator is expressed as follows [16]:

$$P_{in} - P_{out} = J \cdot \omega_m \cdot \frac{d\omega_m}{dt} + D_p \Delta\omega \quad (1)$$

$$\Delta\omega = \omega_m - \omega_g \quad (2)$$

where, P_{in} , P_{out} , ω_m , ω_g , J , and D_p denote, respectively, the input power (analogous to the mechanical input power from the prime mover in a conventional synchronous generator), the inverter output power, the virtual angular frequency, the grid angular frequency (or reference angular frequency), the moment of inertia, and the damping coefficient. In addition, in power systems, the concept of the inertia constant (H) is commonly used as an alternative to the moment of inertia. The inertia constant H is calculated according to the following expression [17]:

$$H = \frac{1}{2} \frac{J \cdot \omega_r^2}{S_r} \quad (3)$$

where H is the grid inertia constant, S_r and ω_r denote the rated power and rated angular speed of all generators in the grid, respectively.

The VSG technology illustrated in Figure 2(b) is based on the frequency–power feedback principle proposed by the VSYNC project. Its objective is to reproduce the inertial response of synchronous generators, thereby enabling distributed energy resources to operate as dispatchable power sources [16, 18, 19]. Compared with conventional droop control, which primarily regulates the steady-state frequency, VSG additionally provides dynamic frequency control [20] by utilizing the derivative of the measured frequency signal to emulate the process of inertial power injection and absorption. This approach allows real-time adjustment of the inverter output power in response to frequency variations.

2.2. Control methods for virtual synchronous generators

This paper adopts the frequency–power response–based VSG control architecture proposed by the VSYNC project, which utilizes grid frequency and ROCOF as inputs. The effectiveness, experimental applicability, and virtual inertia emulation of this structure have been validated through real-time simulations, field tests, islanded grid applications, and wind power systems [21–25]. The detailed VSG control structure based on this approach is illustrated in Figure 2(b). From (1), it can be observed that the ROCOF is represented by the term $\frac{d\omega_m}{dt}$ (Hz/s). In Figure 2(a), the VSG output power is calculated according to the following expression [10]:

$$P_{VSG} = K_D \cdot \Delta\omega + K_I \cdot \frac{d\Delta\omega}{dt} \quad (4)$$

where $\Delta\omega$ and $\frac{d\Delta\omega}{dt}$ respectively represent the deviation of angular frequency and the rate of change of frequency (ROCOF), and K_D and K_I denote the damping coefficient and the inertia constant coefficient. In Figure 2(b), a phase-locked loop (PLL) is employed to measure the system frequency deviation and the ROCOF [26]. Subsequently, based on Equation (4), the reference active power for the inverter can be calculated using the parameters measured by the PLL. From this reference power, the corresponding reference current values are generated and fed to the current controller. Here, by adopting a current control strategy based on the orthogonal two-axis (d–q) reference frame, the d-axis reference current can be calculated as follows [24]:

$$I_d^* = \frac{2}{3} \cdot \left(\frac{V_d P_{VSG} - V_q Q}{V_d^2 + V_q^2} \right) \quad (5)$$

where V_d and V_q are the d-axis and q-axis components of the measured grid voltage, respectively. The q-axis reference current is set to I_q^* , and the reactive power Q is set to zero, since it is assumed that only active power is regulated. Based on the feedback signals from the grid current, the current controller generates the control signals required to operate the inverter. Consequently, the inverter in this case operates as a voltage-source inverter under current control. The coefficients K_D and K_I in Equation (4) can be estimated using the following expressions [11]:

$$K_I = \frac{P_{VSG_nominal}}{\left(\frac{d\Delta\omega}{dt} \right)_{max}} \quad (6)$$

$$K_D = \frac{P_{VSG_nominal}}{\Delta\omega_{max}} \quad (7)$$

where $P_{VSG_nominal}$ is the rated power of the VSG, $\left(\frac{d\Delta\omega}{dt} \right)_{max}$ is the maximum allowable ROCOF, and $\Delta\omega_{max}$ is the maximum allowable angular frequency deviation. From Equations (3), (4), and (6), the emulated virtual inertia constant ($H_{emulated}$) provided by the VSG can be calculated as follows:

$$H_{emulated} = \frac{K_I f_r}{2P_g} \quad (8)$$

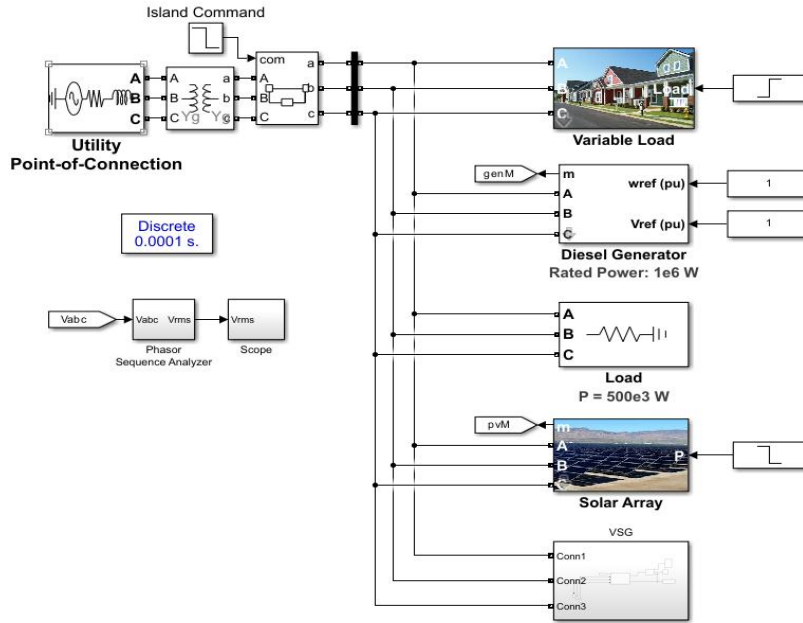


Figure 3. MATLAB/Simulink-based microgrid model.

where f_r is the rated grid frequency, and P_g is the total active power of the entire grid.

3. SYSTEM MODELING

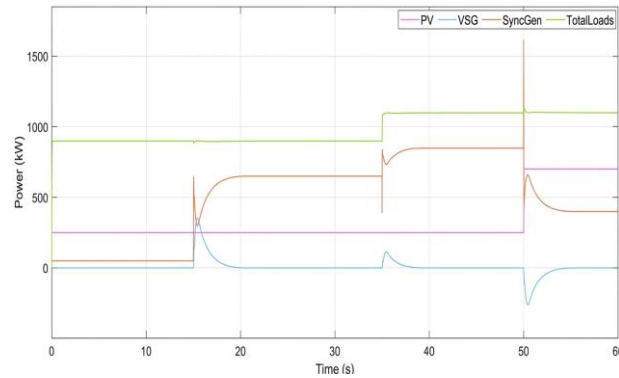
In this section, a microgrid system incorporating a VSG is developed and used for simulation and analysis. Figure 3 illustrates the microgrid system, which consists of loads, a conventional synchronous generator, photovoltaic sources, and a VSG connected to the main grid through a three-phase circuit breaker. The entire simulation model is implemented using MATLAB/Simulink 2023a. The main parameters of the power grid and its components are summarized in Table 1.

Table 1. System parameters for simulation.

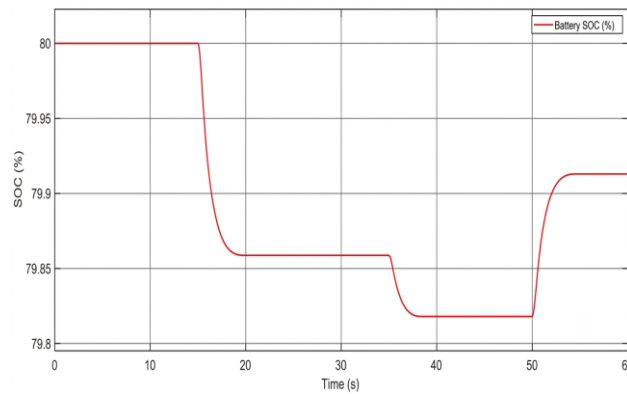
Parameters	Symbol	Value
Grid frequency	f	50 Hz
ROCOF	$ROCOF_{max}$	0.6 Hz/s
Nominal power of diesel generator	$P_{D \text{ nominal}}$	1000 kW
Maximum power of PV system	$P_{PV \text{ max}}$	700 kW
Maximum power of 3-phase dynamic load	$P_{L \text{ max}}$	400 kW
Power of 3-phase static load	P_L	500 kW
BESS nominal power	$P_{BESS \text{ nominal}}$	700 kW
BESS storage capacity	C_{BESS}	100 kWh
SOC upper and lower bounds	$SOC_{min} - SOC_{max}$	10–90%

The simulated microgrid (Figure 3) consists of loads, a conventional synchronous generator, distributed energy sources, and a system-level VSG with a lithium-based BESS utilizing active and reactive power (P/Q) control inputs. The conventional generator is modeled as a salient-pole machine, the photovoltaic system as a three-phase dynamic load simulating electromagnetic transients, and the static and dynamic loads as a three-phase RLC circuit and a P/Q-commanded block, respectively.

4. SIMULATION RESULTS AND DISCUSSION



a) Power exchange in the grid.



b) SOC of BESS.

Figure 4. Simulation results of power exchange in the microgrid.

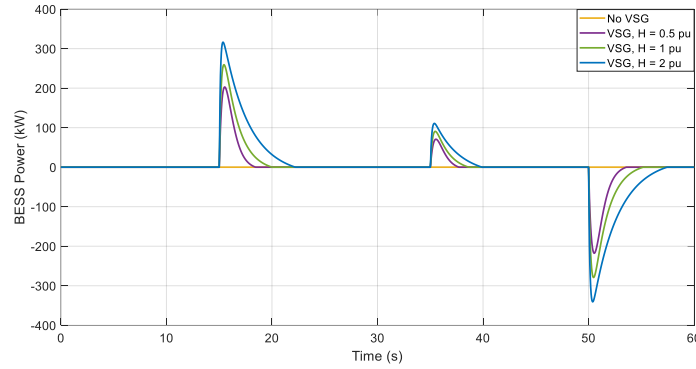
To verify VSG feasibility, the microgrid model (Figure 3) is simulated under various scenarios, primarily in islanded mode where the VSG and a conventional generator maintain stability during load and PV fluctuations. To evaluate its impact, the emulated inertia constant (H_e) is varied while keeping all other parameters constant, following these steps:

- From $t = 0$ to 15 s, the microgrid operates in grid-connected mode.
- At $t = 15$ s, the three-phase circuit breaker is opened via an external control signal, and the microgrid is disconnected from the main grid. From this instant onward, the microgrid operates in islanded mode.
- At $t = 35$ s, the variable load increases by 200 kW of active power.
- At $t = 50$ s, the active power output of the PV system increases by 400 kW.

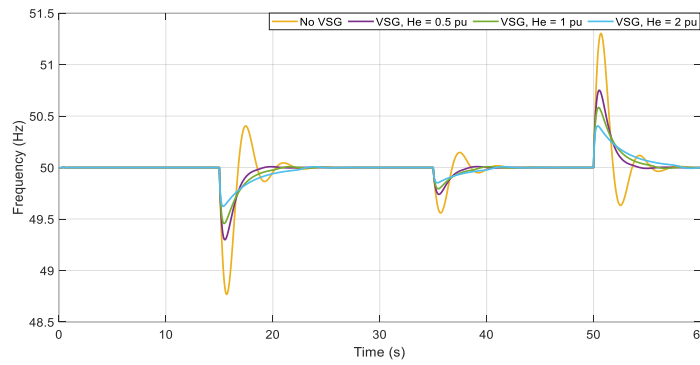
Under this simulation scenario, the K_I parameter of the VSG is first tuned such that the emulated inertia constant H_e of the VSG is equal to 2 p.u. The corresponding simulation results are shown in Figure 4. As illustrated in Figure 4(a), during both grid-connected operation (from 0 s to 15 s) and islanded operation (from 15 s to 60 s), power balance within the microgrid is consistently maintained by the conventional generator and the VSG. Figure 4(b) shows that the VSG's battery energy storage system (BESS) charges and discharges, as indicated by the state of charge (SOC), to compensate for variations in load and generation within the microgrid.

Varying the emulated inertia constant (H_e from 0 to 2 p.u.) reveals that a larger H_e increases

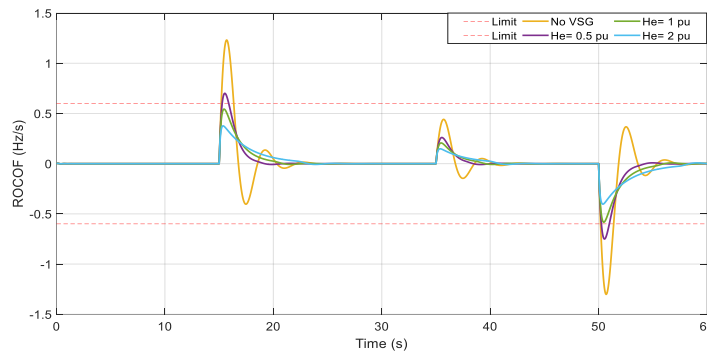
BESS power exchange (Figure 5(a)), significantly reduces grid frequency deviations (Figure 5(b)), and substantially improves ROCOF (Figure 5(c)) compared to the case without a VSG. However, this reveals a trade-off: higher virtual inertia improves frequency stability but increases BESS involvement, leading to higher battery losses and degradation. Therefore, practical microgrid operation requires a careful compromise between frequency support and battery lifetime.



(a) Active power response of the VSG via the BESS.



(b) Grid frequency dynamic response.



(c) Response of the rate of change of frequency (ROCOF).

Figure 5. Frequency response simulation results of the microgrid.

5. CONCLUSIONS

This paper has presented an overview of the structure and control principles of the VSG in microgrid systems, along with the development of a simulation model to evaluate VSG operation in MATLAB/Simulink. Various simulation scenarios and parameter variations of the VSG demonstrate its capability to provide virtual inertia and frequency regulation in a manner comparable to conventional synchronous generators. As a result, frequency oscillations are

mitigated and overall system stability is enhanced under disturbance conditions. These findings indicate that the VSG represents an effective and feasible solution for improving the reliability and controllability of modern power systems with a high penetration of renewable energy sources. Future work will focus on advanced control strategies that achieve optimal operational performance while extending the lifetime of the BESS.

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TÓM TẮT

Mô phỏng ứng dụng của máy phát đồng bộ ảo trong việc nâng cao tính ổn định của lưới điện nhỏ

Nhằm giải quyết các thách thức về độ ổn định hệ thống do sự gia tăng các nguồn năng lượng tái tạo nối lưới qua bộ nghịch lưu, bài báo này trình bày tổng quan về phương pháp điều khiển Máy phát đồng bộ ảo (VSG) trong lưới điện nhỏ và xây dựng mô hình toán học của chúng. Phương pháp đề xuất được kiểm chứng thông qua mô phỏng trên nền tảng MATLAB/Simulink. Kết quả cho thấy VSG cung cấp quán tính ảo hiệu quả, giúp giảm biên độ dao động tần số và nâng cao độ ổn định của lưới điện khi xảy ra sự cố, khẳng định tiềm năng ứng dụng to lớn của VSG trong các hệ thống điện hiện đại có tỷ lệ năng lượng tái tạo cao.

Từ khoá: Máy phát đồng bộ ảo; Năng lượng tái tạo; Quán tính lưới; Lưới điện nhỏ; Mô phỏng.