Simulation Analysis of Simulink-based Inverter Controller in Micro-grids

Lubing Zhao*

School of Automation, Wuhan University of Technology, Wuhan, 430000, China

*Corresponding author: 330441@whut.edu.cn

Abstract. As environmental awareness increases and new energy technologies develop, microgrid systems have garnered significant attention as an important method for operating new energy sources. This trend reflects the growing emphasis on environmental protection. In the process of achieving both independent operation and grid-connected operation, the internal microgrid needs to incorporate an inverter control system equipped with various control methods. The inverter control system is responsible for regulating the inner loop parameters, and the coupling of these parameters will directly impact system stability. The research focus of this article is on microgrid systems that include wind-solar-storage systems. The study primarily employs three control types—constant power control (PQ), virtual synchronous generator control (VSG), and a combination of PQ and VSG control (PQ+VSG)—for simulation analysis to explore system stability. By conducting an in-depth stability analysis, we further understand the characteristics of inverter internal control and grid-connected inverter operation, thereby providing guidance for the design of control systems and ultimately achieving their effective application in power systems.

Keywords: Micro-grid system, PQ control, VSG control, hybrid control.

1. Introduction

In order for human society to survive and develop, energy is an essential component. Since the consumption of non-renewable energy sources such as oil, coal, and natural gas has increased in recent years, environmental pollution problems have steadily worsened. Under this circumstance, the development of new energy technology has been continuously improved, and clean energy based on wind and solar energy has gradually entered the public's field of vision [1].But due to the lower energy density of wind and solar energy than traditional coal-fired power units, and the characteristics of dispersion and uncertainty, micro-grids consisting of distributed power sources, energy storage equipment, distribution facilities, and power loads have become a hot topic [2]. Power electronics are, however, the most common technology for generating renewable energy power. With the growth of renewable energy power generation, more power electronic equipment are being connected to the grid. System stability is negatively affected by these devices' low inertia and lack of damping characteristics [3].

This article mainly studies the effects of using PQ control mode, VSG control method, and PQ+VSG control method on the system stability operation of the system stability under the operating state of the landscape. And use Simulink to simulate the above three inverters control methods, discuss the effects of different inverter control schemes on the stability of the system, and provide ideas for other combined multi -inverter control circuits.

2. Composition and architecture of micro-grid system

Micro-grids are small systems for generating, distributing, and consuming power. There are many components in it, such as distributed power sources, energy storage systems, energy converters, monitoring and protection devices, loads. It is an autonomous system with self-control and self-energy management capabilities [4]. It can effectively realize the output of distributed power supply, improve the reliability of customer power, and achieve power quality performance indicators such as voltage and harmonics [5, 6]. Also, micro-grids have the advantage of being able to connect to an external power grid as well as becoming an island in the event of a large power outage. The typical micro-grid structure is shown in Figure 1.

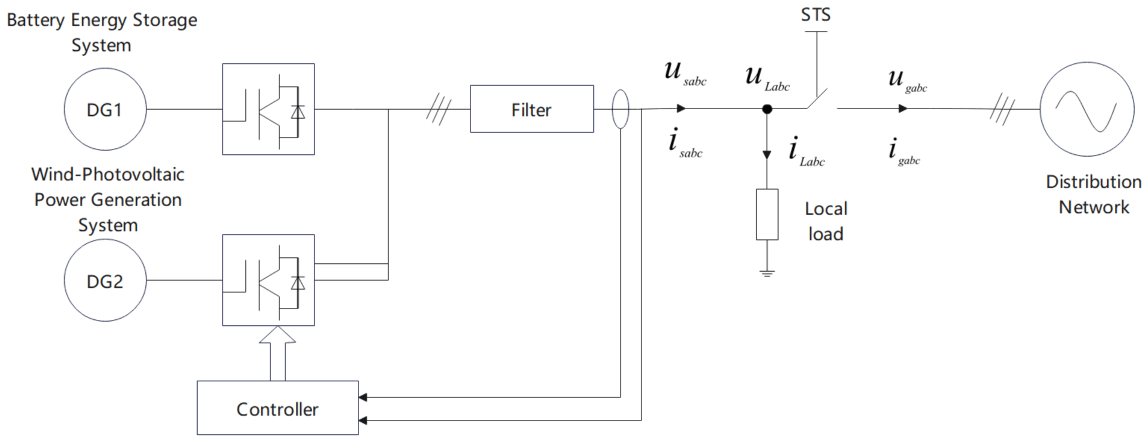


Figure 1 Micro-grid system structure diagram

In the figure, DG is a distributed generator. The DC output end of DG is connected to the DC end of the inverter. Under the action of the control link, the input DC is converted into AC energy, and the energy flows to the load side and the large power grid through the filtering circuit. In some practical application scenarios, to meet electromagnetic compatibility requirements, inverters may be equipped with electromagnetic interference (EMI) filter modules on the DC and AC sides [7]. In a micro-grid system, whether it is connected to the grid or independently supplies power to the load as an island, the stable operation of the micro-grid is the key [8].

This paper is based on the background of isolated micro-grid operation. As shown in Figure 1-1, even if the micro-grid contains an energy storage system, the lack of support from the large power grid will make the micro-grid system highly power-electronic, which will lead to significant characteristics such as low inertia and weak damping [9]. For this reason, a voltage-source inverter is necessary for the isolated micro-grid to support the voltage and frequency.

The four typical control methods of micro-grids are: constant power control (PQ), constant voltage and frequency control (V/f), droop control (Droop), and virtual synchronous generator control (VSG) [10]. In PQ control, the power grid sets the voltage and frequency, while the current controls the output power. Therefore, in essence, PQ control is a current control [11]. Therefore, the voltage control of this article is mainly selected from the three types of controllers, Droop controller and VSG controller. Compared with the V/F controller and Droop controller, VSG control can simulate the speed regulator function of the synchronous generator, which can perform frequency adjustment. In addition, VSG control can provide virtual inertia through energy storage systems, so that the load of the system does not occur without obvious temporary processes. So VSG controller and PQ controller are chosen to study the influence of the parameters of the inner control loop and the line impedance on system stability, as well as the coupling between the two control inverters.

3. Typical control methods for micro-grid operation

3.1. PQ controller

3.1.1 PQ control structure

PQ control is constant power control. In the grid-connected operation mode, according to the power reference value provided by the system, the PQ controller outputs the corresponding active and reactive power, so that the distributed power source can always generate maximum power. The structural block diagram of PQ control is shown in Figure 2.

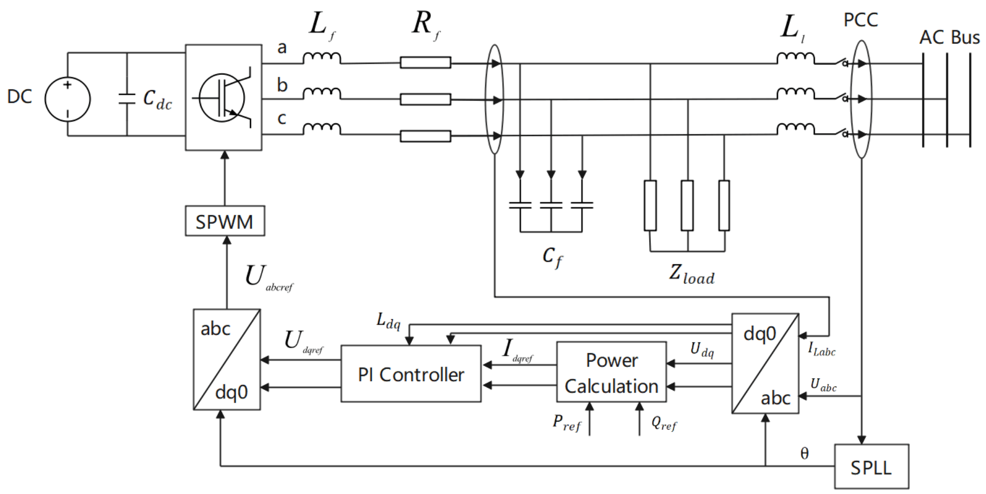


Figure 2 PQ control principal diagram

In the flow chart, the main circuit consists of a DC source or a rectified DC source, an inverter, a three-phase filter circuit composed of L_f, R_f, and C_f, a local load, and a three-phase AC power grid. PQ control consists of three parts: phase-locked loop and dq conversion, power control, and current control. PQ control reads the AC voltage amplitude, frequency, and phase on the bus through the phase-locked loop (SPLL) module to provide a reference for the subsequent coordinate transformation, and performs park transformation on the three-phase current output by the RLC filter and the voltage on the input bus side to obtain U_{dq} andI_{Ldq}.

Output U_{dq} to the power control module to calculate with the active and reactive reference values to obtain the current reference value I_{dqref}, and then introduce I_{Ldq} and the current reference value I_{dqref} through the PI controller of the current loop to obtain the reference voltage value U_{dqref}. After the park inverse transformation, the voltage reference value U_{abcref} in the three-phase coordinate system is obtained. Finally, the SPWM drive signal is generated to control the inverter, thereby completing the PQ control of the inverter [12].

3.1.2 Mathematical model of PQ controller

The voltage and current output from the inverter are decomposed into U_d, U_q, I_d, I_q in the synchronous rotating coordinate system, and the output active power P and reactive power Q are expressed as follows:

$$\begin{cases} p = \frac{3}{2}(u_d i_d + u_q i_q) \\ q = -\frac{3}{2}(u_d i_q - u_q i_d) \end{cases} \tag{1}$$

As a consequence of the grid voltage being oriented to the d-axis, it follows that the voltage on the q-axis is zero, and therefore the active and reactive powers can be expressed as follows:

$$\begin{cases} p = \frac{3}{2} u_d i_d \\ q = -\frac{3}{2} u_d i_q \end{cases} \tag{2}$$

3.2. VSG controller

3.2.1 VSG control structure

By embedding the mathematical model of the synchronous generator into the inverter's control algorithm, VSG simulates the operation of a stationary power electronic device as a rotating motor. By simulating the primary frequency and voltage regulation of the synchronous generator, it dampens rapid fluctuations in voltage and frequency, distributes power automatically, and operates synchronously in a grid. As a result of VSG technology, inverters are comparable to synchronous generators in terms of external characteristics and operation [13]. However, in addition to the advantages of having the same functions as synchronous generators, VSG control also brings problems such as power oscillations generated by synchronous generators [14]. The typical VSG control structure is shown in Figure 3.

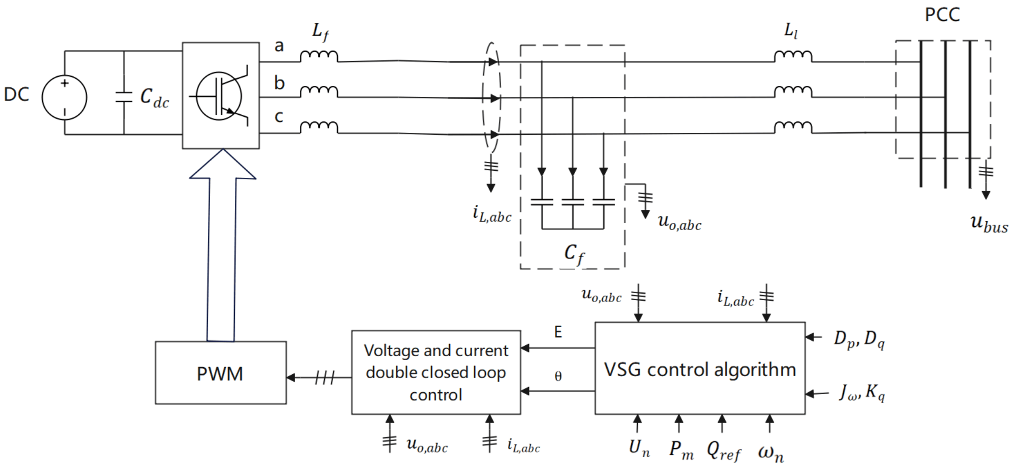


Figure 3 Typical VSG control structure

In Figure 3, the main circuit consists of a DC source or a rectified DC source , an inverter, a filter inductor L_f, a filter capacitor C_f, a line inductor L_l and a three-phase AC power grid. $i_{L,abc}$is the three-phase current output by the filter inductor;$u_{o,abc}$is the three-phase voltage output by the filter capacitor;$J_\omega$is the inertia coefficient; u_{bus} is the three-phase line voltage on the AC bus side; $D_q, D_p$are the reactive droop coefficient and damping coefficient of VSG respectively;P_m, Q_{ref} are the mechanical power and reactive power reference values of VSG respectively; $U_n$is the rated voltage; $K_q$is the reactive inertia coefficient; E is the amplitude of the VSG electromotive force; θis the phase of VSG.

3.2.2 Mathematical model of VSG controller

The traditional three-order model of VSG is as follows:

$$\begin{cases} \frac{d\omega}{dt} = \frac{1}{J}\left[P_m - P_e - D_p(\omega - 1)\right] \\ \frac{d\delta}{dt} = \omega_B(\omega - 1) \\ \frac{dE}{dt} = \frac{1}{T_0}\left[Q_{ref} - Q_e + D_q(E_0 - E)\right] \end{cases} \tag{3}$$

Among them, ω is the virtual angular velocity; t is the time; J is the inertia time constant of VSG; E_0 is the virtual rated electromotive force. Then the formula for the mechanical power P_m of the virtual synchronous generator is:

$$P_m = P_{ref} + D_p'(1\text{-}\omega) \tag{4}$$

Among them, P_{ref} is the active power reference value; D_p' is the active power droop coefficient. Then the active power P_e and reactive power Q_e output by VSG is:

$$\begin{cases} P_e = \frac{EU\sin\delta}{X_1} \\ Q_e = \frac{EU\cos\delta}{X_1} - \frac{U^2}{X_1} \end{cases} \tag{5}$$

Where, X_1 is the equivalent reactance between VSG and the grid.

3.3. Parallel operation of PQ controller and VSG controller

This paper studies the influence of the coupling effect between different control inverters on system stability by connecting the PQ control circuit and the voltage source type VSG control circuit in parallel to the grid. The structural diagram of the island micro-grid is shown in Figure 4.

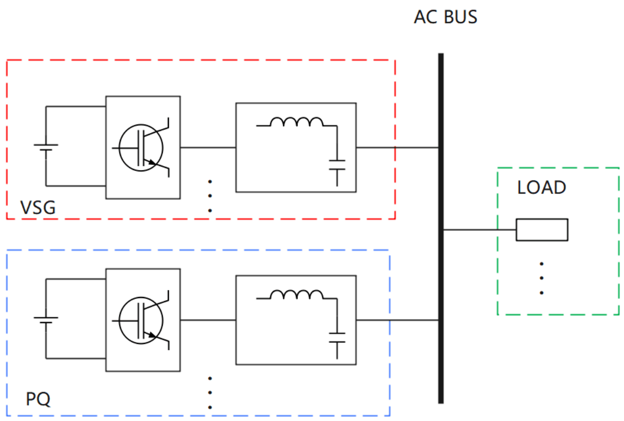


Figure 4 Structure diagram of isolated island microgrid

4. Simulation Verification

Depending on the structure of the island in Figure 4, simulation is performed in Simulink. First, the PQ control inverter is connected separately to observe the correctness of the output waveform verification PQ control model. Then connect the VSG control inverter with a load, and also observe whether the output waveform verification simulation is correct. Finally, in the island mode, two different control inverters are carried in parallel to observe the output waveform and verify the power and frequency adjustment performance of the VSG control inverter by changing the load.

4.1. Simulink simulation platform

Simulink is a visual simulation tool based on MATLAB that covers simulation and model design in the fields of industrial automation, signal processing, power electronics, etc.

Simulink is a block diagram environment that provides users with a rich toolbox, allowing users to directly use the models in the toolbox to build by dragging and dropping, so that users can easily build electrical model simulations. Furthermore, Simulink also provides a graphical editor for modeling and simulating dynamic systems using user-defined module libraries.

In the theoretical study of the problem, compared with traditional experimental methods, it has many advantages to use Simulink for model building and simulation. First of all, Simulink simulation technology can provide more flexible and efficient experimental solutions, support the simulation of discrete, continuous and mixed signals, reduce dependence on experimental venues and equipment, and avoid safety issues that may occur in actual experimental scenarios. Secondly, the Simulink platform can handle the simulation of complex systems of multi -field and interdisciplinary disciplines. Aside from that, Simulink is tightly integrated with MATLAB, so users can use MATLAB's powerful simulation analysis and visualization tools, batch processing scripts, modeling environment customization, signal parameters, and test data directly.

4.2. Single inverter simulation verification

4.2.1 PQ controller simulation

The Simulink built according to the structure diagram of the PQ controller is shown in Figure 5.

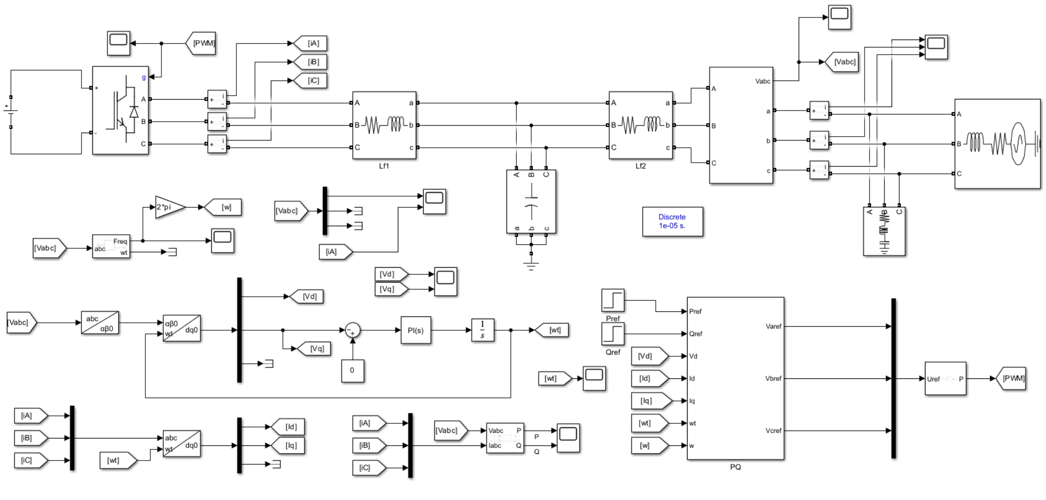


Figure 5 PQ controller simulation circuit diagram

The simulation parameters are shown in Table 1.

Table 1 PQ simulation model parameters

Parameter	Value
V_{dc}	1000V
L_{f1}	1000μH
L_{f2}	500μH
C_f	500μF
R_f	0.01ohms
P_{ref}	40kW
Q_{ref}	0kVar

According to the PQ mathematical model mentioned above, we can get the three-phase voltage waveform of the phase-locked loop in Figure 6.

Figure 6 Three-phase voltage waveform

The output three-phase current waveform is shown in Figure 7.

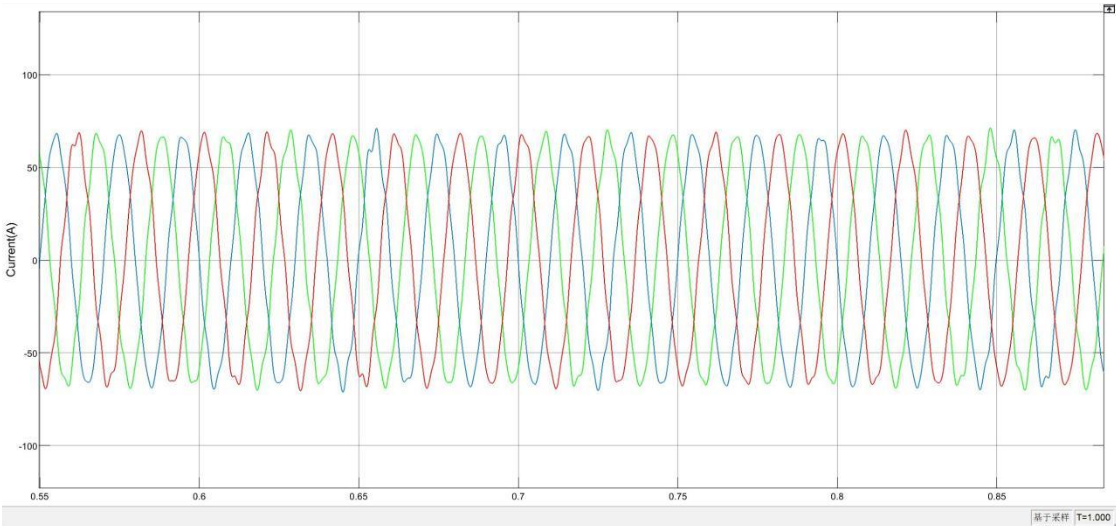


Figure 7 Three-phase current waveform

From the waveform diagram, it can be judged that the three-phase voltage and current waveforms output by the PQ controller when it is running alone are normal, but due to the presence of more capacitors and inductors, the current waveform fluctuates slightly at the peak value. Perform FFT analysis, and the THD of the current signal is shown in Figure 8.

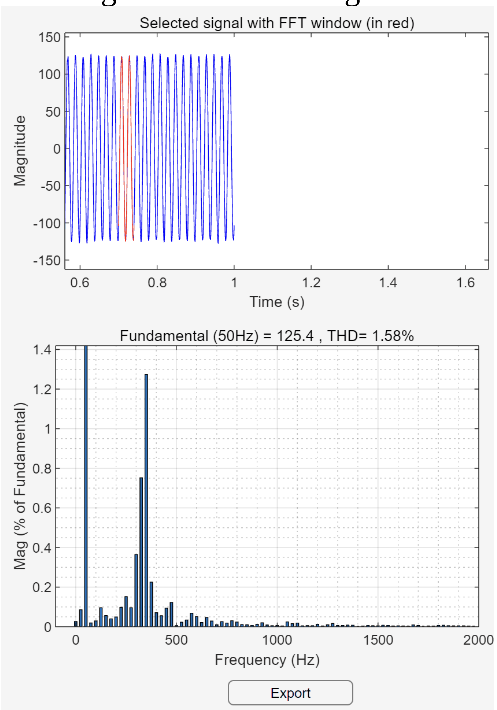


Figure 8 FFT analysis

The current waveform of 0.7s was taken for FFT analysis, and the THD was 1.58%, which meets the grid requirement of less than 5%.

4.2.2 VSG control simulation

VSG control includes the following three modules: 1. The VSG power outer loop (active power-frequency droop link rotor motion equation reactive power-voltage droop link) synthesizes the three-phase reference voltage; 2. In a double closed loop, voltage and current are tracked quickly and without static errors; 3. PWM modulation mode to generate waves.

Since the off-grid VSG simulation model is relatively complex, the simulation is built and displayed according to the above three modules. The Simulink built according to the main circuit structure diagram of the VSG controller is shown in Figure 9.

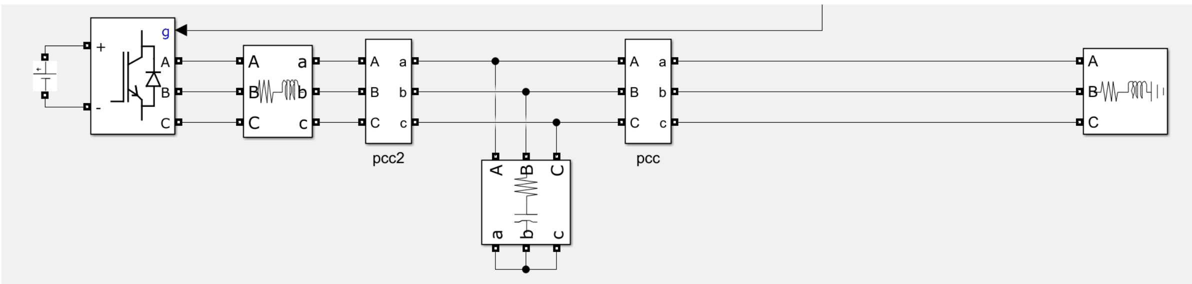


Figure 9 VSG main circuit diagram

Among them, g connects the PWM signal generation module to input and output PWM waveform. The PWM signal generation model is shown in Figure 10.

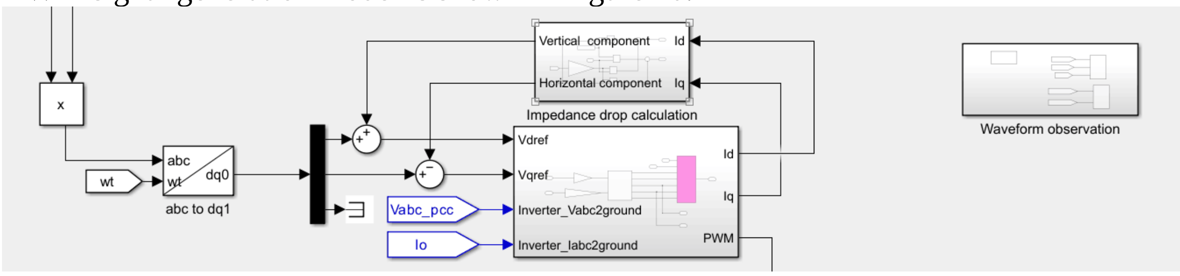


Figure 10 Overall control circuit diagram

The VSG control model is shown in Figure 11.

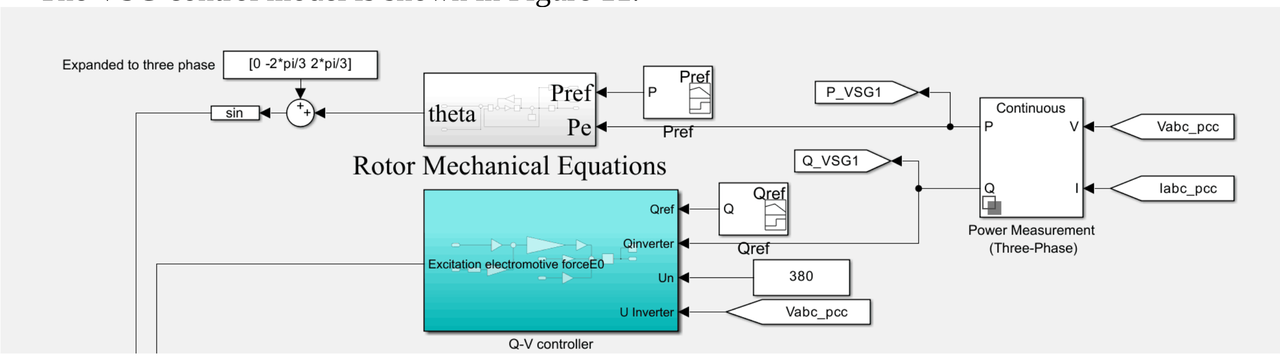


Figure 11 VSG control circuit diagram

Among them, the three-phase sinusoidal signal value and the excitation electromotive force are input into the PWM generation module through the multiplication input module. The simulation parameters are shown in Table 2.

Table 2 VSG simulation model parameters

Parameter	Value
P/Q	120kW/10kVar
V_{dc}	2000V
L_{f1}	200μH
R_f	0.05ohms
R_l	0.5ohms
C_f	10μF

The voltage and current waveforms of the VSG control simulation output are shown in Figure 12.

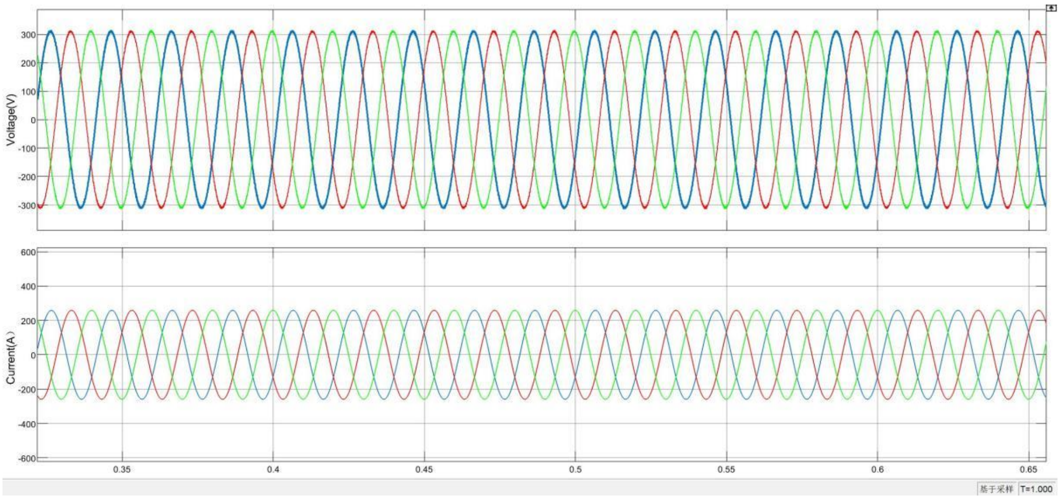


Figure 12 Voltage and current waveforms of VSG control output

When the VSG controller runs alone, the output current and voltage waveforms are normal. FFT waveform analysis is shown in Figure 13.

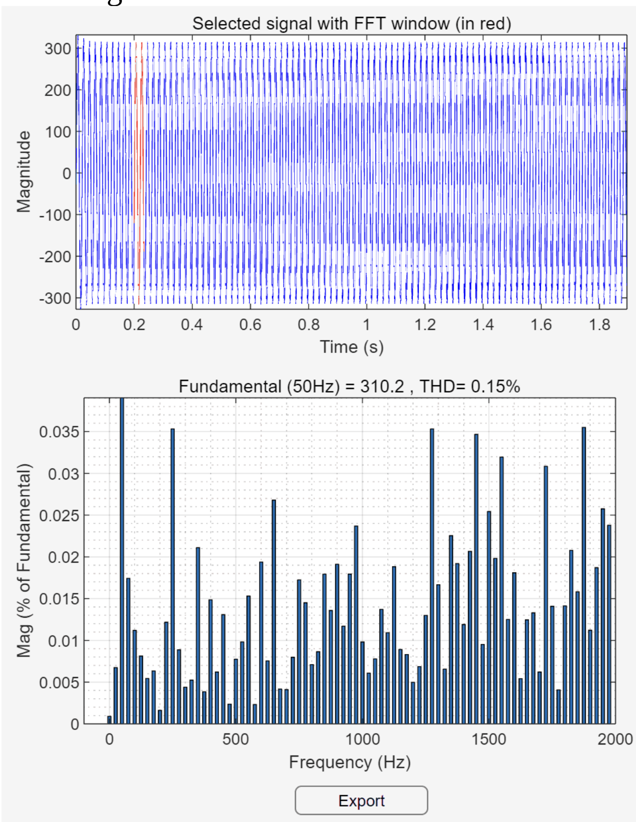


Figure 13 FFT analysis

The current waveform of 0.2s was taken for FFT analysis, and the THD of the current was measured to be 0.15%, which meets the grid access standard.

4.3. Simulation of parallel operation of PQ controller and VSG controller

In the simulation modeling of PQ control and VSG control parallel, this article adopts a T -type three -level inverter as the control object. There is a significant reduction in switching loss, since the switch stress is only one-half of the two levels. A higher-level output brings the inverter's output voltage waveform closer to sine waves compared with the three levels of inverters, the T-type topology structure is simple and high in 4-30kHz. Therefore, the local microgrid model consisting of two T-type three-level inverters running in parallel based on VSG control and PQ control is shown in Figure 14.

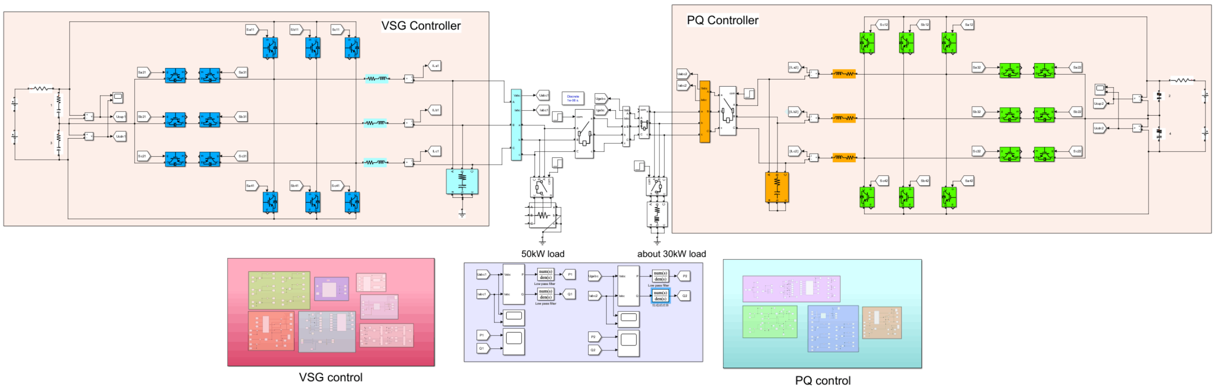


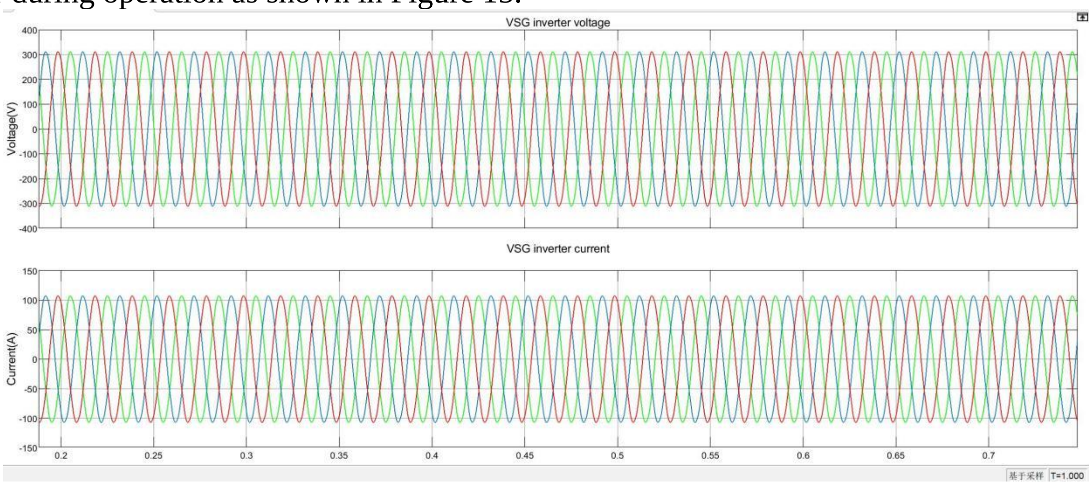
Figure 14 Local microgrid model with VSG control and PQ control in parallel

The simulation parameters are shown in Table 3.

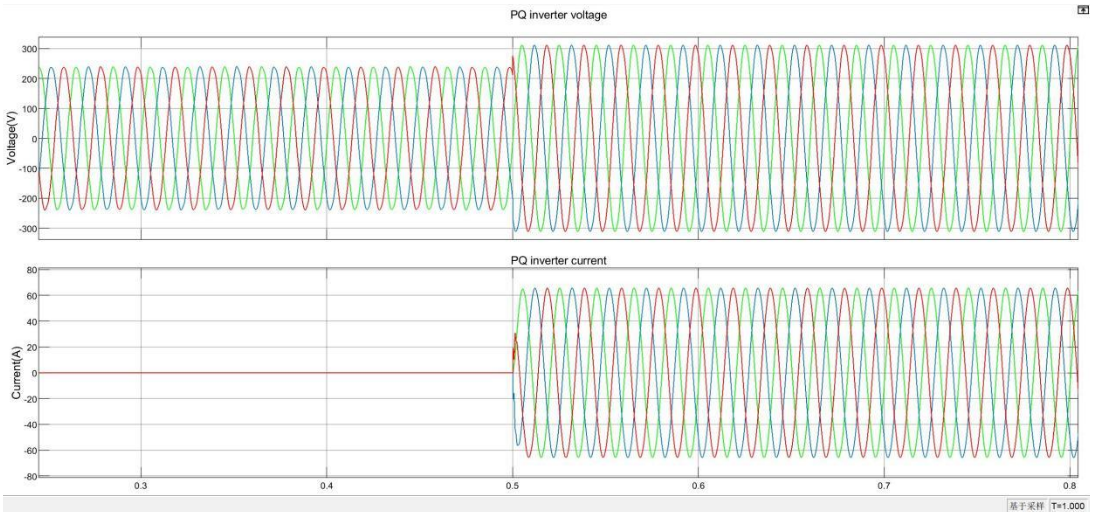
Table 3 PQ VSG parallel simulation parameters

Parameter	Value
V_{dc}	350V
R_{line}	0.001ohms
$R_{f,abc}$	0.1ohms
$L_{f,abc}$	5mH
C_f	1.5mF
R_{load1}	2.9ohms
R_{load2}	5ohms
L_{load2}	1.5mH
P_{ref1}/Q_{ref1}	50kW/0kVar
P_{ref2}/Q_{ref2}	30kW/2kVar

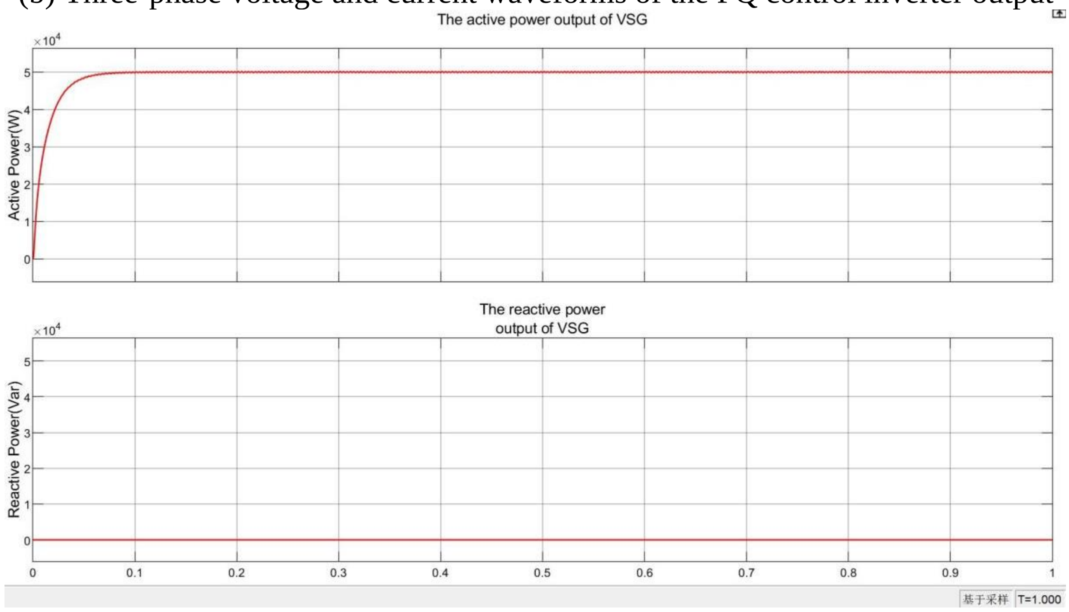
It is operated in island mode. In the first 0.5s, only the first inverter controlled by VSG is put into operation. At 0.5s, the second inverter controlled by PQ is put into operation. Observe the stability of the system in the parallel mode of PQ and VSG controlled inverters, as well as the output voltage and current waveforms and output power waveforms of the VSG controlled inverter and the PQ controlled inverter during operation as shown in Figure 15.



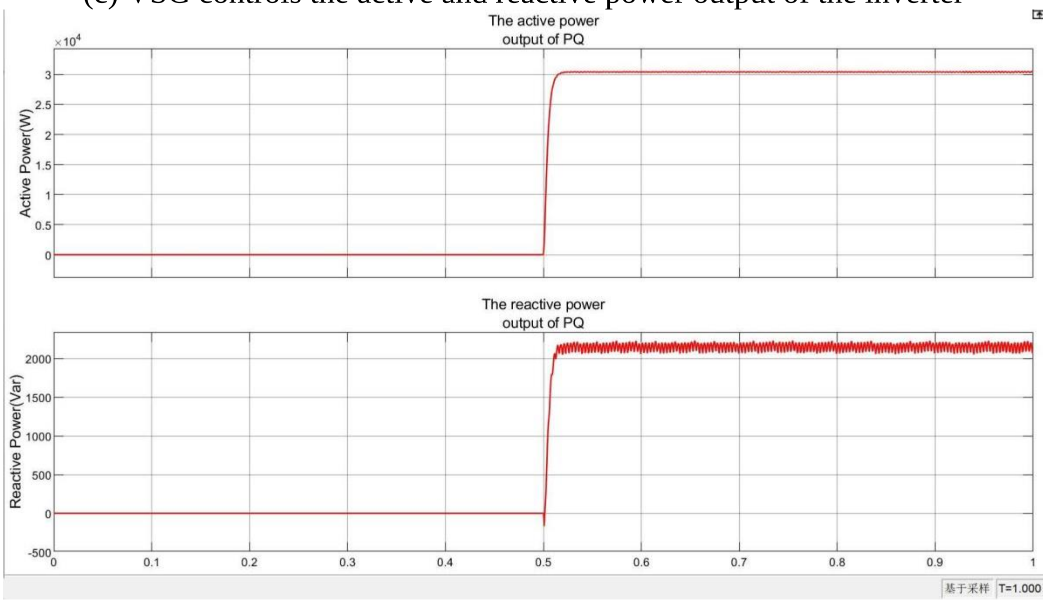
(a) Three-phase voltage and current waveforms of the VSG-controlled inverter output



(b) Three-phase voltage and current waveforms of the PQ control inverter output



(c) VSG controls the active and reactive power output of the inverter



(d) PQ controls the active and reactive power output of the inverter

Figure 15 VSG and PQ control the voltage, current and power output of the inverter during parallel operation

It can be analyzed from the figure that the VSG control inverter is relatively stable throughout the process. When 0.5S is controlled by the external signal control, the circuit breaker is closed to the inverter of the PQ control of the PQ control, the voltage current of the VSG control inverter And it has no obvious changes in the power and has a certain stability. At 0.5s, connect to the PQ control inverter, the voltage of the PQ control one side increases, the peak value is similar to the side of the VSG control, and it maintains a stable operation within 0.01s; In the s, it is stable.The VSG control side is in the grid-connected state, and its active power and reactive power are the same as the set P_{ref} and Q_{ref}.PQ control on the side of the side and non -effective power without power is generated when it is parallel at 0.5s. When the contribution increases, the powerless power also increases, but compared. At the time, there will still be a relatively obvious small range fluctuation. Compared with the simulation effect of a single inverter in the previous article, the fluctuation may be related to the coupling effect between the two inverters, which causes a small range of fluctuations in the power.

5. Conclusion

This article introduces the structural model and related control methods containing the micro -grid system containing the landscape storage. It analyzes the structural model and mathematical model of PQ control and VSG control, and on the Simulink simulation platform Simulation verification, the correctness of the two control methods was verified by the model building and debugging. Then perform the inquiry of the stability of the PQ control inverter and the VSG control inverter in parallel. From the perspective of the simulation results, the effect of coupling effects between the connected inverters has relatively small effects on voltage current, and on the power of power, the power of power The impact is more obvious, especially the non -effective power of the PQ control inverter, which will cause certain fluctuations during stable operation. Due to the idealization of the island scene mentioned in this article, the single control method cannot well meet the operation of the island micro -grid. There is indeed a coupling effect between parallel transportation of the two control methods, but there is no more specific influencing factors. Further exploration. The research on multiple types of control inverters is conducive to improving the construction of the micro-grid system and improving the stability of the micro-grid system.

References

[1] Kaiye G, Tianshi W, Chenjing H, et al. A Review of Optimization of Microgrid Operation. Energies, 2021, 14(10): 2842-2842.

[2] Cai Cong. Research on coordinated control of isolated microgrids. Northeast Electric Power University, 2023.

[3] Tang Niang, Sheng Chao, Chen Meng, et al. A review of virtual synchronous generator technology. China Southern Power Grid Technology, 2016, 10(11): 30-38.

[4] Miguel A, Junior V, Deyslen M, et al. A Review of Low-Voltage Renewable Microgrids: Generation Forecasting and Demand-Side Management Strategies. Electronics, 2021, 10(17): 2093-2093.

[5] Monika S, Saeed P, Ariya S, et al. Reliability aspects in microgrid design and planning: Status and power electronics-induced challenges. Renewable and Sustainable Energy Reviews, 2022, 159.

[6] Sidarth G T, Mehdi S, Elmira J, et al. Role of optimization techniques in microgrid energy management systems—A review. Energy Strategy Reviews, 2022, 43.

[7] Zeng Zheng, Zhao Rongxiang, Tang Shengqing, et al. A review of advanced grid-connected inverters for decentralized access to renewable energy. Proceedings of the CSEE, 2013, 33(24): 1-12 +21.

[8] Majumder R. Some Aspects of Stability in Microgrids. IEEE Transactions on Power Systems: A Publication of the Power Engineering Society, 2013, 28(3): 3243-3252.

[9] Wang Zili, Chen Yandong, Li Xueping, et al. Frequency difference-free coordinated control strategy for multiple virtual synchronous generators in isolated microgrids. Power System Protection and Control, 2024, 52(07): 12-23.

[10] K. B D, B. B, J. K D V, et al. A Voltage and Frequency Droop Control Method for Parallel Inverters. IEEE Transactions on Power Electronics, 2007, 22(4): 1107-1115.

[11] Liang Huamin. Research on distribution network fault characteristics considering the impact of photovoltaic access capacity. Nanjing University of Posts and Telecommunications, 2022.

[12] Wang Senfeng. Modeling and stability analysis of inverter parallel system based on VSG and PQ control. Yanshan University, 2022.

[13] Yang Ding, Yu Yang, Sun Jiahang, et al. Distributed optimization of microgrid integrating VSG frequency regulation and economic dispatch. Electrical Engineering, 2024, (04): 34-42 +64.

[14] Shintai T, Miura Y, Ise T. Oscillation Damping of a Distributed Generator Using a Virtual Synchronous Generator. IEEE Transactions on Power Delivery, 2014, 29(2): 668-676.