Parallel Control Strategy for Inverters Based on Virtual Impedance (Postprint)

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Date: 2019-03-05T00:00:00+00:00

Abstract

When multiple inverters operate in parallel, differences in design parameters, connection line impedances, and other factors among the inverters cause the equivalent line impedances of each inverter module to vary, often leading to system circulating currents and resulting in system instability. This paper analyzes the parallel operation system of inverters and proposes a circulating current suppression method based on virtual impedance for parallel inverter operation.

Full Text

Research on Inverter Parallel Control Strategy Based on Virtual Impedance

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Abstract

When multiple inverters operate in parallel, differences in design parameters and connection impedance among individual inverters lead to variations in their equivalent line impedance, often resulting in system circulating currents that cause instability. This paper analyzes parallel inverter operation systems and proposes a circulating current suppression method based on virtual impedance for parallel inverter operation.

Keywords: Parallel inverter, circulating current analysis, master-slave control, virtual impedance

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1 Introduction

In recent years, microgrids incorporating numerous distributed generation (DG) units have become a research focus worldwide. Distributed generation sources in microgrids primarily include wind power, photovoltaics, energy storage batteries, diesel generators, and fuel cells [1], most of which connect to the microgrid through inverters. Energy storage bidirectional inverters are specialized conversion devices for energy storage systems that interface with battery banks and the public grid. During grid load valleys, they convert AC power from the grid to DC power to charge the battery bank; during peak load periods, they convert DC power from the batteries back to AC power meeting grid requirements, thereby achieving peak shaving and valley filling to ensure normal grid operation.

Multi-module parallel operation technology represents a crucial pathway for switching inverter power supplies to evolve toward high-power applications and serves as a key enabling technology for the transition from traditional centralized power supply to distributed power supply modes [2]. Unlike conventional synchronous generator parallel systems that achieve automatic synchronization of output voltage frequency and phase, PWM inverter parallel systems lack this self-synchronization capability [4]. To ensure stable and reliable parallel operation of PWM inverters, each inverter module must satisfy three fundamental conditions: (1) Output voltage amplitude, phase, and frequency must be consistent. Accumulation of slight frequency differences causes periodic variations and waveform distortion in parallel system output amplitude; unequal amplitudes induce circulating currents among parallel units; phase differences destabilize output and may cause severe shocks during paralleling. (2) Within the range of input voltage and load variations, each inverter module must share load current equally with good dynamic response characteristics. Unequal load sharing causes thermally stressed modules operating under overload conditions for extended periods, reducing system reliability. (3) Reliable protection measures are required. Besides internal fault protection, rapid corrective actions must be taken when circulating currents or synchronization anomalies occur to ensure system reliability.

Parallel inverter applications should demonstrate four primary advantages: (1) Highly flexible system capacity configuration through modular capacity combinations, providing users with various power ratings. (2) Reduced current stress on power switching devices and improved reliability. As each module shares the load power, switching device current stress is significantly reduced, not only overcoming power level limitations imposed by switching devices but also enhancing the stability and reliability of individual inverter modules. (3) Standardized inverter modules with high power density facilitate industrial production. Parallel inverter modules manufactured through standardized production exhibit good consistency and interchangeability. (4) High system redundancy and maintainability. Through redundant design, the system achieves fault tolerance and redundancy functions, facilitating maintenance.

Due to multiple parameters such as amplitude and phase in inverter outputs, parallel inverter operation is more challenging than DC power module paralleling. Under ideal parallel operation, each inverter module’ s output voltage has equal amplitude, equal frequency, and identical phase, meaning the voltage difference between modules is zero at any instant. However, in practical parallel inverter systems, output voltage instantaneous values among modules are often unequal due to circuit parameter differences, load variations, or inherent control system characteristics. Voltage differences create circulating currents within the system, adversely affecting inverter system stability, reliability, and internal power devices. In severe cases, circulating currents can damage power devices, cause system collapse, and lead to power supply interruption. Therefore, effective circulating current suppression measures constitute the key to parallel inverter operation control [3].

2 Parallel Inverter Equivalent Circuit Analysis

The equivalent circuit model for two parallel inverter modules [5] is shown in Figure 1. U_1 and U_2 represent the fundamental components contained in the SPWM voltage waveforms output by the two inverters; U_{11} and U_{22} are their respective output terminal voltages; U_0 is the parallel node voltage (i.e., load voltage); L_1 with C_1 and L_2 with C_2 are the output filter inductors and capacitors of the two inverters; rL_1 and rL_2 are the connection resistances of the filter inductors; r_1 and r_2 represent parallel connection (wire) resistances; Z_0 is the common load.

[Figure 1: see original paper] Inverter parallel operation equivalent circuit model

Since connection wire resistance is typically very small, rL_1, rL_2, r_1, and r_2 are neglected to simplify analysis. Based on Figure 1, the following basic circuit equations can be written:

$$\begin{aligned} U_1 - j\omega L_1 I_{L1} &= U_0 \\ U_2 - j\omega L_2 I_{L2} &= U_0 \\ I_{C1} &= j\omega C_1 U_0 \\ I_{C2} &= j\omega C_2 U_0 \end{aligned}$$

where I_{C1} and I_{C2} are the currents flowing into capacitors C_1 and C_2, respectively.

When $C_1 = C_2 = C$ and $L_1 = L_2 = L$, we can derive:

$$I_H = \frac{U_{11} - U_{22}}{2Z}$$

From the above relationships:

$$I_{L1} = \frac{I_0}{2} + j\omega C U_0 + \frac{U_1 - U_2}{2j\omega L}$$

From equation (2), the following conclusions can be drawn: When $U_1 = U_2$, I_{L1} = I_{L2} = (I_0/2) + jωCU_0, and the two inverters share load current equally. When $U_1 \neq U_2$, I_{L1} and I_{L2} consist of both load current components and circulating current components, resulting in unequal load current sharing between the two inverters. When U_1 and U_2 have the same phase but different amplitudes, the circulating current appears as a reactive component —capacitive for the inverter with higher voltage and inductive for the inverter with lower voltage. When U_1 and U_2 have equal amplitude but different phases, the leading phase inverter' s circulating current component is a positive active component (outputting active power), while the lagging phase inverter' s circulating current component is a negative active component (absorbing active power). When U_1 and U_2 differ in both phase and amplitude, the circulating current component contains both reactive and active components.

3 Circulating Current Analysis in Parallel Inverter Systems

Considering the circulating current impact caused by differences in output characteristics among inverter units, assuming U_{11} and U_{22} are standard sinusoidal waves under static conditions and ignoring waveform distortion effects, we obtain from Figure 1:

$$\begin{aligned}
U_0 &= (I_{01} + I_{02})Z_0 = I_0 Z_0 \\
U_{11} &= U_0 + I_{01} r_1 \\
U_{22} &= U_0 + I_{02} r_2 \\
U_0 &= \frac{r_2 + r_2/Z_0}{r_1 + r_1/Z_0} U_{11} + \frac{r_1 + r_1/Z_0}{r_2 + r_2/Z_0} U_{22}
\end{aligned}$$

If $r_1 = r_2 = r$ and r Z_0, the above equation simplifies to:

$$U_0 \approx \frac{1}{2}(U_{11} + U_{22})$$

Defining the circulating current as I_H = (I_{01} - I_{02})/2, and since I_0 = I_{01} + I_{02}, we have:

$$I_{01} = \frac{I_0}{2} + I_H, \quad I_{02} = \frac{I_0}{2} - I_H$$

Therefore, the system circulating current is:

$$I_H = \frac{I_{01} - I_{02}}{2} = \frac{U_{11} - U_0}{2r} - \frac{U_{22} - U_0}{2r}$$

Because the output voltages of the two inverters are similar but still exhibit differences, and the line impedance is very small, a slight voltage difference causes significant system circulating current. The waveform shows that the current value caused by circulating current reaches thousands of amperes. Without appropriate suppression measures, this would cause severe damage to the system and power devices.

4 Parallel Inverter Control Analysis

Research on parallel inverter operation technology primarily focuses on two categories: interconnected parallel control (including centralized control, master-slave control, and distributed logic control) and non-interconnected parallel control (mainly through droop characteristics to achieve parallel control without interconnections) [7]. This paper employs a widely applied master-slave control strategy for multi-inverter control.

The master-slave control principle is illustrated in Figure 2, taking two inverters as an example for study. In the figure, u_{ref} is the voltage reference value, u_{of} is the voltage feedback value; G_v(s) and G_i(s) are the voltage regulator and current regulator; i_{LM} is the current value generated by the master unit; i_{LS} is the current value of the slave unit [8]. i_{LM} simultaneously serves as the current reference value for the slave unit, which adjusts based on i_{LM} to track the master unit’ s current value, thereby achieving current sharing.

[Figure 2: see original paper] Master-slave control schematic

A simulation model was built in Matlab/Simulink, where the two inverters employ voltage-type full-bridge inverter circuits with a 200V DC-side voltage, ensuring output voltage amplitude can reach \$±\$100V to meet simulation requirements. The modulation wave duty cycle is 0.5, and the load is purely resistive at 10Ω. To facilitate voltage value capture, a filter function can be implemented at the master unit voltage output for low-pass filtering.

The output voltage waveform is shown in Figure 3. The output current waveforms of the two inverters are shown in Figures 4 and 5. The simulation results demonstrate that although the two inverter output voltages are similar, slight differences still exist. Combined with very small line impedance, these minor voltage differences cause system circulating currents reaching thousands of amperes, which would cause extreme damage to the system and power devices without corresponding suppression measures.

[Figure 3: see original paper] Inverter output voltage waveforms
[Figure 4: see original paper] Inverter 1 output current waveforms
[Figure 5: see original paper] Inverter 2 output current waveforms

5 Parallel Control Analysis with Virtual Impedance

In parallel inverter systems, different line lengths result in different line impedances—longer lines have relatively larger resistance than reactance. Consequently, traditional control strategies generate significant system circulating currents. To improve parallel inverter system safety and stability, the external series inductance method can be employed (adding inductors in series at inverter outputs) to effectively suppress circulating currents. However, achieving good suppression requires large inductors, increasing inverter size, weight, and cost while causing substantial line losses and low efficiency [9]. Therefore, this paper introduces virtual impedance technology to reconstruct inverter output impedance.

Generally, virtual impedance has two forms: virtual inductance and virtual resistance. Virtual inductance makes the inverter equivalent impedance appear inductive, while virtual resistance makes it appear resistive. When adding inductive virtual impedance, the system becomes susceptible to high-frequency harmonic currents, causing significant voltage drops and degrading steady-state performance. In low-voltage microgrids, line impedance has a high resistance-to-inductance ratio, making lines appear resistive. If the inverter equivalent impedance is constructed to be inductive, large virtual inductance is required. In contrast, the virtual resistance form is clearly suitable for low-voltage microgrid control. Therefore, this paper adopts virtual resistance to construct inverter output impedance [10].

Virtual impedance technology involves adding virtual impedance to voltage and current dual-loop control to construct inverter output impedance that meets system requirements. In the aforementioned simulation model, virtual impedance was introduced for verification. Simulation results are shown in Figures 6 through 8, where Figure 6 shows output voltage waveforms with virtual impedance, and Figures 7 and 8 show output current waveforms with virtual impedance.

The results show that the system output voltage reaches the expected value of 50V, but the current value far exceeds expectations, causing unstable output power. This phenomenon primarily occurs because the virtual impedance value is not properly designed. After redesigning the virtual impedance value, the simulation results demonstrate that the output voltage waveform still meets expectations, and the current values of the two inverters stabilize, significantly reducing system circulating currents and facilitating safe inverter operation and system stability.

[Figure 6: see original paper] Output voltage waveforms under virtual impedance
[Figure 7: see original paper] Inverter 1 output current waveforms under virtual impedance
[Figure 8: see original paper] Inverter 2 output current waveforms under virtual impedance

6 Conclusion

This paper briefly analyzed the basic conditions that parallel-operated inverters must satisfy, conducted specific analysis of the parallel system equivalent circuit, and performed theoretical calculations of parallel system circulating currents to identify the root causes of circulating currents. A simulation model was built to visually demonstrate the impact of system circulating currents on stability. To eliminate circulating current effects, virtual impedance was introduced for suppression and tested in the simulation model. Simulation analysis demonstrates that introducing virtual impedance can effectively suppress system circulating currents and improve system steady-state performance.

References

[1] Li Jianlin, Xu Shaohua, Hui Dong. A review of stability analysis and control strategy of multi-parallel PCS for hundred MW level energy storage power station[J]. Proceedings of the CSEE, 2016, 36(15): 4034-4046.

[2] Zhou Xiaoxin, Lu Zongxiang, Liu Yingmei, et al. China' s future power grid development model and key technologies[J]. Proceedings of the CSEE, 2014, 34(29): 4999-5008.

[3] Kan Jiarong, Xie Shaojun, Wu Yunya. Power decoupling control strategy for parallel-connected inverters without interconnections[J]. Proceedings of the CSEE, 2008, 28(21): 40-45.

[4] Shao Mingqiang. Study on parallel control strategy of microgrid inverter[J]. Electricity and Energy, 2016(3): 304-307.

[5] Wang Wenjun, Li Bin, Zhou Bo. A master-slave modified auxiliary inverter parallel control mode study[J]. Inverter World, 2016(3): 60-63.

[6] Zhang Qinghai, Peng Chuwu, Chen Yandong, et al. A micro-grid multi-inverter parallel operation control strategy[J]. Proceedings of the CSEE, 2012, 32(25): 126-132.

[7] Xu Shungang, Xu Jianping, Cao Taiqiang. Control of parallel operating inverter with voltage and current closed-loops[J]. Electric Power Automation Equipment, 2009, 29(10): 103-106.