Research on Topology and Control System of High Power Grid Simulator

Houxiang Li*, Yongming Zhang, Hongyu Zhai
School of Electrical Engineering Shanghai DianJi University Shanghai, China

*Correspondence Author: lihouxiang@shiep.edu.cn

Abstract. Grid simulator can simulate the output of various types of power grid failure to test wind power grid-side equipment, in the design of high-power grid simulator, due to the switching frequency restrictions, will affect the control bandwidth, resulting in the power grid simulator system performance decline. Therefore, the modular multi-level converter (MMC) with higher equivalent switching frequency is used on the inverter side of the grid simulator, and the bridge arm circulation suppression strategy based on the second-order generalized integrator (SOGI) and vector scale integral (VPI) resonant controller is proposed for the internal bridge arm circulation of the converter. Finally, based on RT-LAB, the network simulator controller hardware in the ring (CHIL) experimental platform is built and experimented, the experimental results show that the design of high-power power grid simulator system can simulate the output to obtain the required grid failure.

Keywords: Grid simulator; power grid failure; second-order generalized integrator; vector scale integral resonance controller; controller hardware in the ring.

1. Introduction
In recent years, with the continuous improvement of the power level of wind power generation systems, power grid companies in various countries have put forward stricter requirements for the integration of wind power generation systems into the power grid. The loss of power support leads to cascading accidents, so it becomes very important to study the support ability of the wind power generation system to the grid when the grid fails [1-3]. However, grid faults for testing equipment cannot be generated in a normal power grid. Therefore, there is an urgent need to study a high-power multifunctional power grid simulator system that can simulate various grid faults.

Literature [4] first proposed the concept of a power grid simulator and established a single-phase power grid simulator system. Through a virtual circuit orthogonal to the actual circuit, the control of the output voltage without static difference is realized, and then the voltage fault of the voltage change is simulated. Literature [5] proposes a scheme of power grid fault simulation power supply using programming technology, but it is not suitable for high-power situations; Literature [6] uses a three-phase back-to-back topology, but this topology is three-phase without It is difficult to simulate a single-phase grid fault in the mid-line system, and the power level is also low. Literature [7] proposes the idea of controlling the fundamental wave and harmonic separately, and then couples the fundamental wave module and the harmonic module through an injection transformer group. Load
power supply; In the literature [8], a unified root-mean-square feedback control is adopted to test the grid amplitude, frequency deviation and voltage fluctuation, but the extreme conditions of voltage sag are not simulated. In summary, the current research on power grid simulators is mainly focused on low voltage levels and there are few studies on related control strategies. For this reason, this paper proposes a high-power multi-functional power grid simulation based on a modular multi-level structure. The topology structure of the inverter and the control method for suppressing the circulating current on the inverter side, and the power grid simulator simulation model containing the control strategy is built in Simulink. The simulation results show that the proposed control strategy can effectively suppress the circulating current of the bridge arms. The loop experiment simulates the output power grid fault.

2. Modular multi-level power grid simulation topology

Applying high-power converters in the high-voltage field to the inverter side of the grid simulator can increase the output voltage and power level of the inverter side, but the low switching frequency of the system will limit the bandwidth of the grid simulator and affect the system response speed. In order to improve the performance of the power grid simulator, this paper proposes a topology suitable for high-power power grid simulators, as shown in Figure 1 below.

The relatively novel AC/DC/AC topology structure is adopted. When wind power is connected to the grid, energy will be injected into the grid. Therefore, the grid simulator is required to operate in four quadrants. Therefore, the rectifier side adopts small output voltage ripple and fast dynamic response. The three-phase voltage-type PWM rectifier of this kind of rectifier can make the energy generated by the active load be fed back to the grid to realize the bidirectional flow of energy. In order to improve the power level of the power grid simulator and achieve the requirement of single-phase independent control of the power grid simulator, an improved modular multi-level inverter is adopted on the inverter side. Due to the existence of a common DC bus, four-quadrant operation can be realized and output filtering is possible. The link adopts LC filter to filter the AC voltage output by the inverter, and output a high-precision, low-harmonic test voltage to test the wind power equipment under test.

Using the double closed-loop control based on feedforward decoupling on the rectifier side can output a stable and fast response DC voltage. The performance of the grid simulator mainly depends on the inverter side connected to the wind power equipment under test. The modular multi-level inverter is studied, and the control part of the rectifier side will not be repeated. The topology of the inverter side of the power grid simulator is shown in Figure 2 below.
The topology of the inverter side of the power grid simulator is shown in Figure 2 above, where the sub-modules are half-bridge sub-modules, each of the upper and lower arms of each phase is connected to N sub-modules, $C_0$ is the capacitance of the sub-module, $L_p$ is the inductance of the bridge arm, and $R_p$ is Bridge arm resistance, $U_{dc}$ is the DC bus voltage, SM is the sub-module. Due to the modular design, low-voltage power devices can be used to achieve large-capacity, high-voltage analog requirements. In addition, it is possible to control the number of sub-modules put into operation or improve the topological structure of the sub-modules according to the technical index requirements of the power grid simulator, so as to realize the control of the output voltage and power level.

3. Design of Inverter Side Control System of Power Grid Simulator

Ignoring the bridge arm resistance $R_p$, it can be seen from the circulating current expression established in [9] that the AC component of the circulating current is expressed as:

$$I_{circ} = \sum_{n=1}^{\infty} nI_{circ} \cos(n \omega t + \theta_{circ})$$

$$= \frac{N}{2wC_0L_p} \left[ \frac{1}{4} M \cos \theta \sin 2wt 
- \frac{3}{4} I_m M \sin(2wt - \theta) - \frac{1}{2} I_m M \sin \theta 
+ I_{circ} \left( \frac{2}{n} \cos(mwt + \theta_{circ}) + \sum_{n=2}^{M} \left( \frac{1}{n-1} \cos((n-2)wt + \theta_{circ}) \right) \right)
+ \frac{2n}{n^2-1} \cos(mwt + \theta_{circ}) - \frac{1}{n+1} \cos((n+2)wt + \theta_{circ}) \right]$$

For the above formula, $\omega$ is the system angular frequency, $I_{circ}$ is the peak of the nth-harmonic of the circulating current, $\theta_{circ}$ is the initial phase of the nth-harmonic, $U_c$ is the sub-module capacitor voltage, $I_m$ is the peak output current, and $\theta$ is the output voltage and output current. $U_{dc}$ is the peak value of the output phase voltage, and $M = 2U_{dc}/U_m$ is the defined modulation ratio. It can be seen from equation (1) that the internal current of MMC during normal operation mainly includes direct current and circulating current components, and the circulating current components do not contain odd-numbered harmonics, because the proportion of high and even harmonics in the circulating current is very small. Therefore, the second harmonic component is mainly used for the suppression of circulating current.

The traditional proportional integral (PI) control cannot achieve static-free control of the AC signal. The ideal proportional resonance (PR) can only eliminate the harmonics at a specific frequency and
amplify the noise near the resonance frequency. In order to enable the system to better suppress the circulating current, multiple PR controllers are required to adjust the even sub-circulating current, which is not conducive to the realization of the controller [10]. In order to achieve no static error tracking of harmonic current components at the resonance frequency, a circulating current suppression scheme based on SOGI and VPI resonance controllers is designed, where the transfer function of VPI in the static coordinate system is:

\[
G_{VPI} = \frac{2K_p s^2 + K_
u s}{s^2 + (2w_0)^2}
\]  

(2)

In formula (2), \( K_p \) and \( K_
u \) are the controller parameters, and \( w_0 \) is the fundamental angular frequency.

**Fig. 3** Block diagram of circulating current suppression based on SOGI and VPI resonant controller

In Figure 3, in order to realize the suppression of the double frequency circulating current component, and the resonant frequency is \( 2w_0 \), \( i_p \) and \( i_l \) are the upper and lower bridge arm currents, and the average value can be used to obtain the interphase circulating current. The double frequency in the circulating current is extracted by SOGI. For the circulating current component, the circulating current reference value \( i_{\text{cir ref, } i} \) is set to 0, and the tracking is adjusted by the VPI resonance controller to obtain the compensation signal \( u_{\text{com, } i} \) of the corresponding bridge arm reference voltage, thereby achieving the suppression of the MMC circulating current.

Adding the VPI resonant controller to the MMC controlled system model can get the closed-loop current control block diagram based on the VPI controller as shown in Figure 4.

**Fig. 4** Block diagram of closed loop flow control based on VPI

The parameter setting of the VPI resonant controller is based on the zero-pole cancellation and band-pass filter, which can make the zero of the VPI resonant controller and the pole of the control object cancel each other [11]. The relationship between the controller parameters and the bridge arm inductance \( L_p \) and the bridge arm resistance \( R_p \) can be obtained as:

\[
\frac{K_p}{K_
u} = \frac{R_p}{L_p}
\]  

(3)

Combining equation (3) and Figure 4, the closed-loop transfer function can be obtained as:

\[
G_{VPI,c}(s) = \frac{G_{\nu}(s)G_{\nu}(s)}{1 + G_{\nu}(s)G_{\nu}(s)} = \frac{2K_p s}{L_p s^2 + 2K_
u s + L_p (2w_0)^2}
\]  

(4)

It can be seen from equation (4) that when the inductance and resistance of the bridge arm are determined, the performance of the circulating current suppression strategy mainly depends on \( K_
u \).
Therefore, draw the Bode diagram of the closed-loop transfer function when $K_p$ takes 0.1, 0.5, 1, 5, and 10, as follows Shown in Figure 5.

![Bode diagram of the closed-loop transfer function of the system](image)

**Fig. 5** Bode diagram of the closed-loop transfer function of the system

It can be seen from Figure 5 that when gradually increasing, the transfer function of equation (4) can achieve 0dB amplitude and 0° phase response at 100Hz, indicating that the use of VPI resonant controller can achieve the second harmonic at 100Hz No static error tracking of current component. The gain of the closed-loop transfer function of the system decreases rapidly with the increase of $K_p$, which ensures the selectivity of the frequency. At the same time, the system bandwidth increases and the system response speed is improved. After comprehensive analysis, take $K_p$ as 10, and put it into equation (3) to obtain $K_v$ as 333.3.

In order to verify the topology of the grid simulator and the circulating current suppression algorithm proposed in this article, a three-phase high-power grid simulator simulation circuit was built in MATLAB/Simulink. The rectifier side adopts double closed-loop control based on feedforward decoupling to output stable DC Voltage, The inverter side adopts the circulating current suppression strategy of this article, and the modulation strategy is carrier phase shift PWM, The system parameters are as follows: single-phase rated capacity is 3.3KVA, $R_p=0.1$, $U_{dc}=800V$, $N=4$, $C=2mF$, $L_p=3mH$, $U_{in}=200V$, system fundamental frequency is 50Hz, system equivalent switching frequency is 10KHz.

![Waveform and FFT analysis before and after circulating current suppression](image)

**Fig. 6** Waveform and FFT analysis before and after circulating current suppression
Figure 6(a)(b) is the circulating current waveform of the upper and lower bridge arms of phase A before the circulating current suppression is activated. The circulating current suppression based on the SOGI and VPI resonant controllers did not start within 0.3s of the simulation, and the circulating current reached 10.48A at this time. Figure 7 (c) FFT analysis of the output waveform without circulating current suppression and found that the double frequency component and quadruple frequency component contained in the waveform are 39.28% and 4.87%, respectively. After 0.3s, the circulation suppression control strategy was started, the peak value of the circulation was reduced to 5.108A, the second harmonic component was reduced to 0.65%, and the high and even harmonic content was also reduced, which basically suppressed the circulation in the bridge arm. AC component.

4. Experiment
In order to further verify the correctness of the topology and control system of the high-power grid simulator proposed in this article, FPGA is used as the controller and RT-LAB as the main circuit of the simulation to build a CHIL single-phase 3.3KVA power grid simulator experiment based on RT-LAB. Platform to test the functions of the power grid simulator.

Set the single-phase output voltage adjustment range: 0~600V, and the frequency change range: 5-90Hz. Figure 7(a) is the load voltage output by the LC filter when the load is 3.3KVA, and the voltage amplitude is 480V. 7(b) is the analog output voltage distortion. The output voltage contains 3% of the 3rd harmonic, 1% of the 5th harmonic, 0.8% of the 7th harmonic, and 1.6% of the 11th harmonic.

Figure 8(a) is the simulated output voltage swelling experiment. The voltage swelling fault occurs when the setting is 1s, and the voltage amplitude rises from 480V to 520V and remains stable. Figure 8(b) shows the extreme situation when the analog voltage drops to 0, that is, the analog zero voltage ride through. The voltage drops to 0 at 1s and returns to the normal voltage after 0.1s.

5. Concluding remarks
Aiming at the problems of low switching frequency, low control bandwidth, and slow response speed of high-power grid simulators, a modular multi-level grid simulator topology is proposed to improve the system output power level and system equivalent switching frequency. In order to simulate a stable and high-performance output voltage, the SOGI and VPI resonant controllers are used to suppress the internal high-even-order circulating current components. This circulating current strategy does not require phase-to-phase decoupling, phase-locked loop, coordinate transformation and other links, and the circulating current suppression effect is obvious. Finally, an RT-LAB-based controller hardware-in-the-loop experiment platform was built to simulate low-voltage ride-through, frequency
failure and other experiments, completed the basic function test, and verified the correctness and effectiveness of the theory.

References
[1] Han Rong, Xu Qianming, Ding Hongqi, Luo An. Modular multi-level mid-high voltage power grid simulator and its control[J]. Transactions of the Chinese Society of Electrical Engineering, 2018, 33(S1): 165-175.
[2] Liu Xiaoxi. Research on System Topology and Control Strategy of Megawatt Power Grid Simulator [D]. Hefei University of Technology, 2020.
[3] Zhu Hong, Zhang Xing, Li Fei, Li Ming, Wang Chengyue. Research on megawatt multifunctional power grid simulator system with line impedance simulation[J]. Acta Solar Energy, 2020, 41(05): 281-292.
[4] Zhang R, Cardinal M, Szczesny P, et al. A Grid Simulator with control of single-phase power converters in DQ rotating frame [C]// Power Electronics Specialists Conference, 2002. pesc 02. 2002 IEEE 33rd Annual. IEEE, 2002.
[5] Cheng M, Zou Z, Wang Z, et al. Fractional-order repetitive control of programmable AC power sources [J]. Iet Power Electronics, 2014, 7(2): 431-438.
[6] Karuppaswamy A B, Gulur S, John V. A Grid Simulator to Evaluate Control Performance of Grid-Connected Inverters. IEEE, 2015.
[7] Wang Ying, Li Jiesi, Liu Fang, Zhang Xing. Research on multifunctional power grid simulator [J]. Power Electronics Technology, 2011, 45(03): 29-31+34.
[8] Li Yufei, Wang Yue, Wu Jinlong, et al. Control strategy for fluctuating voltage generation of cascaded H-bridge converter [J]. Transactions of the China Electrotechnical Society, 2015, 030(009):46-52.
[9] Chang Guoxiang, Yuan Dongdong. Suppression strategy of circulating current in quasi-PIR modular multilevel converter [J]. Journal of Heilongjiang University of Science and Technology, 2021, 31(03): 325-331.
[10] Jing Xuchuan, Cao Yilong, Jiang Youhua. MMC circulation suppression strategy based on PR+virtual impedance compound control [J]. Journal of Shanghai Electric Power University, 2021, 37(03): 221-225.
[11] Wang Yufeng, Sun Xiaopeng, Wang Yupeng, et al. Application of VPI resonant controller in SAPF[J]. Journal of Liaoning Technical University, 2017(01): 96-102.