Low voltage ride-Through strategy based on virtual synchronous generator control

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Abstract. Inverters controlled in virtual synchronous generator(VSG) method is able to operate in both grid-connected mode and islanding mode. Due to this characteristic, this paper put forwards a low voltage ride-through(LVRT) strategy which is based on VSG control. If the grid voltage sags, VSG can limit the output current amplitude and meanwhile inject reactive power to the grid. Once the voltage drop time exceeds the maximum ride-through time, VSG would smoothly switch to islanding mode and continues to carry loads independently. The proposed strategy achieves a control algorithm unity between normal operating and grid voltage sag status in grid-connected mode. Simulations can support the validity of the strategy.

1. Introduction

These guidelines, With the increasing penetration of distributed power, more and more power sources using inverters as interfaces are connected to the grid[1-2]. Traditional grid-connected inverter with fast response, low inertia and less damping, is difficult to participate in grid frequency and voltage regulation[3-4].To this end, scholars have proposed virtual synchronous generator(VSG) technology that can through controlling, the inverter possesses the same mechanism and external characteristics as what synchronous generator has through controlling, to provide inertia and damping for the grid[5-6].

The current researches about VSG are usually focusing on normal operation condition, but rarely involved in the aspects of fault ride-through[7-8]. Literature[7] classified the types of grid voltage drops in detail, and analyzed the worst operating conditions that each drop may cause to develop corresponding control strategies to compensate, with some reference value. Literature[8] used balanced current controller that transfer the stator terminal voltage reference to current reference value through the filter circuit equation. Thereby, current regulator was introduced to control negative sequence current directly in grid voltage imbalance condition.

On the basis of previous researches, considering that VSG can operate in islanding condition independently, when the grid voltage sag time exceeds the allowed limit value, VSG could smoothly switch to islanding mode from grid-connected LVRT mode and continue to carry loads. As for mode smooth switching algorithms, there are many references from both converter itself and the system level[9-10].

This paper analyzes the operation principles of synchronous generators(SG) in the first place, pointing that to make the VSG have the same external characteristics with the SG, the VSG should meet the operation equations through controlling. Then, according to the depth and the time of grid voltage sag during LVRT process, it is divided into different operation stages and the corresponding

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control strategies are designed in every stage and their switching process. Finally, simulations have verified the effectiveness of the LVRT strategy.

2. VSG control

2.1. Synchronous generator operation principles

In a synchronous generator[11], the operation satisfies the following equations (1) to (4):

$$E_A = K\phi\omega \tag{1}$$

$$V_\phi = E_A - jX_s I_A - R_A I_A \tag{2}$$

$$\begin{cases} P = \dfrac{3V_\phi E_A \sin\delta}{X_s} \\ Q = \dfrac{3V_\phi (E_A \cos\delta - V_\phi)}{X_s} \end{cases} \tag{3}$$

$$\begin{cases} T_m - T_e = J\dfrac{d\omega}{dt} \\ T_m = \dfrac{P_m}{\omega} \\ T_e = \dfrac{P_e}{\omega} \end{cases} \tag{4}$$

where E_A is the armature voltage, K is the proportional factor, ϕ is the magnetic flux, V_ϕ is the stator output voltage, $X_s$is the synchronous reactance, R_A is the synchronous resistance, δ is the phase angle between $E_A$and V_ϕ, Tm is the mechanical torque, T_e is the electromagnetic torque, P_m is the input mechanical power, P_e is the inductive electromagnetic power.

These four formulas completely describe the operation principle of a synchronous generator.

2.2. Analysis of VSG model

Virtual synchronous generator model should meet the operating principles of synchronous generator as expounded before and speed controller and excited controller are designed to satisfy different control demands. A speed controller is used to regulate the input mechanical power of the prime-mover to maintain the spinning speed whereas an excitation controller is utilized to regulate the armature voltage and the output reactive power.

If the DC side provides a stable input power to the inverter, VSG can operate in both grid-connected mode accessing to the grid and islanding mode with loads. Depending on the control requirements, VSG models can be constructed in various methods and the corresponding controllers will differ a lot.

3. LVRT Strategy

3.1. LVRT requirements analysis

At present, the standard of energy storage unit LVRT is not unified yet. Unlike PV and wind power, if the depth and duration time of the voltage drop do not meet the requirements of LVRT, inverters can switch to islanding mode and continue to operate.

Based on this, it can be divided into three operational stages: the grid-connected stage if the grid voltage is in normal range; the LVRT stage if the grid voltage meets the ride-through requirement and the islanding stage if the grid voltage exceeds the ride-through requirement.

3.2. LVRT algorithm

As mentioned above, the use of direct current control method can limit inductor current magnitude directly and control the reactive component of inductor current so as to satisfy the requirements of LVRT current limit and reactive power compensation.

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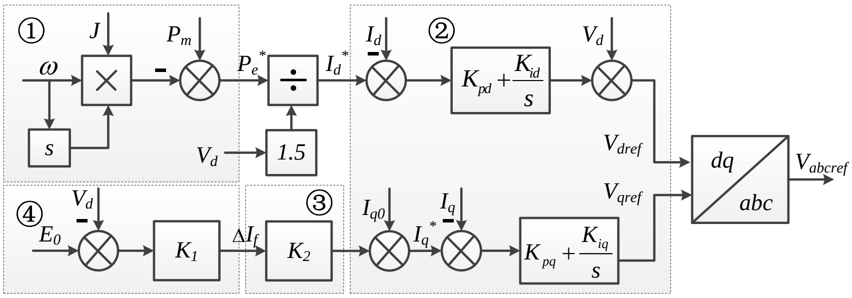

Figure 1. Grid-connected VSG model.

①is the rotor motion equation.

②is the terminal voltage equation.

③K2 characterized the V-curve which is obtained from simultaneous equations of (1) and (2) as reactive power control design basis.

④is the excitation controller.

In this algorithm model, ω is the angular velocity of the grid, V_d,V_q,I_d,I_q are the dq axis component of the grid voltage and inductor current respectively, E_0 is the rated grid voltage d-axis component, I_{q0} is the basis reactive current component,J is the rotational inertia. ω is achieved from phase locking loop that in grid-connected mode the speed controller is replaced by PLL block.

The reactive power instruction is regulated according to the grid voltage amplitude in real time.Without a separate LVRT algorithm to calculate the homologous current command based on the current grid voltage amplitude, this model is a unity of normal grid-connected operation model and LVRT algorithm. Selecting the appropriate parameters K_1 and K_2, the requirement of reactive power can be fully satisfied. When the voltage drop reaches the maximum depth, the VSG issues the maximum capacitive reactive power.

In order to facilitate islanding VSG algorithm design, take K_2=1, K_1=K. Active power instruction is set in accordance with the reactive power in equation (5):

$$P_m = \min\left(P_m, (\sqrt{S_{\max}^2 - Q^2}) \times \frac{V_d}{E_0}\right) \tag{5}$$

If the active current component keeps rated, the maximum reactive current component is calculated in equation (6) and the corresponding grid voltage drop is computed in equation (7). This means, if the grid voltage sags beyond 0.47V_N, the output active power should be restricted to ensure the reactive current component injection.

$$I_q = \sqrt{(1.1I_{Nm})^2 - I_{Nm}^2} = 0.46I_{Nm} \tag{6}$$

$$\Delta V = \frac{I_q}{K} = \frac{0.46\times 1.13}{1.1}V_N = 0.47V_N \tag{7}$$

3.3. Islanding VSG algorithm

Close switches S_2 and S_3, then the islanding VSG model is derived as shown in Figure 2.Among them, ① to ④have the same meanings with those in section B and ⑤ is the speed controller.

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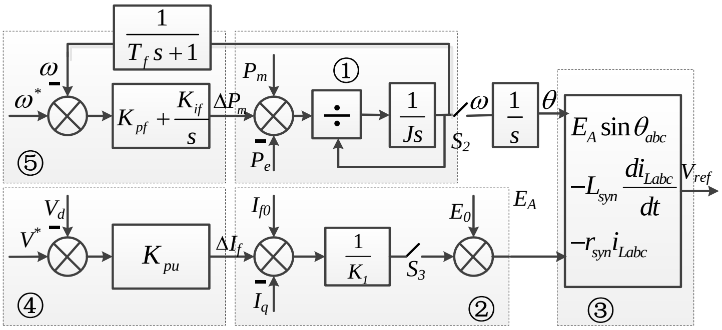


Figure 2. Islanding VSG model.

This algorithm ensures stable supports of frequency and voltage when off-grid, and normal operations of the loads can be guaranteed.

Since K_2=1, where I_f and I_q are equal in magnitude, that the field current feedback value I_f in armature equation (1) can be detected by the q-axis component of filter inductor current.

When the grid voltage drop depth and duration time exceed the LVRT requirements, the VSG should switch to islanding mode and operate continuously. The smooth switching algorithm is designed as Figure 3.

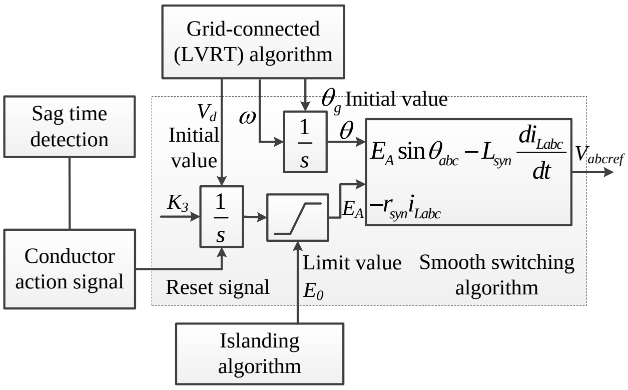


Figure 3. Smooth switching algorithm.

This algorithm takes the angular velocity of the PLL in grid-connected mode as the reference angle, the real-time grid voltage amplitude V_d as the initial value of the voltage integral block and the reset signal is provided by the contactor action signal. This control block guarantees the moment the contactor operates, the output of the integral block is consistent with the grid. The integral time constant K_3 is set based on the depth of voltage drop and the recovery time T_r whereas the limit of integrator is equal to the voltage reference value E_0 in islanding mode that ensures the output of integrator reach the armature voltage magnitude if saturated.

Considering equation (8), the setting of parameter T_r should take the regulation speeds of speed controller and excited controller into account to guarantee a stable output voltage and frequency in recovery process. Parameter K_3 can be optimized to adjust itself automatically according to the actual depth of voltage drop ΔV_N. The contactor opens after a time of T_r, the voltage restores, then removes the PLL and closes S_2 and S_3.

$$K_3 = \frac{\Delta V_N}{T_r} \tag{8}$$

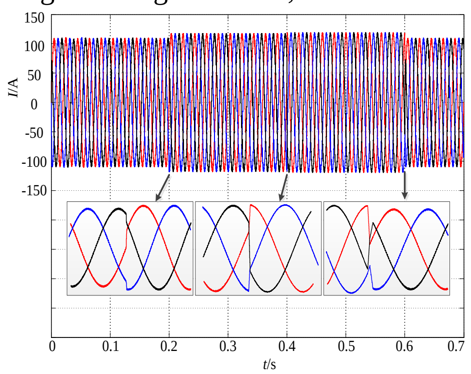
4. Simulation Results

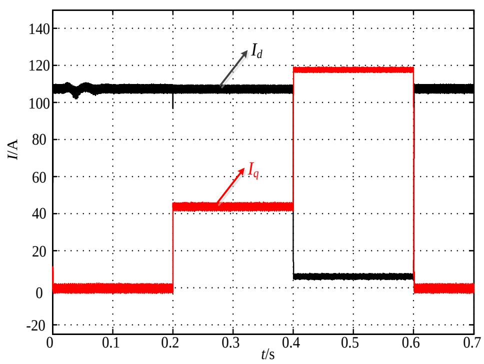
Several simulations are carried out in MATLAB/ Simulink environment to study the effectiveness of the proposed LVRT algorithm. Simulation parameters are shown in table 1.The LVRT process is shown in Figure 4. Three sub figures in Figure 4(a) are the inductor current during transient process.

Table 1. Simulation parameters.

DC voltage	700V	Rated power	50kVA
AC rms phase voltage	220V	Current limit value	1.1pu.
Filter inductance	0.5mH	Rotational inertia	0.5kg · m^2
Filter capacitance	50μF	Switching frequency	10kHz
Line impedance	0.05mH+0.05 Ω	Parameter T_r	0.2s

During 0-0.2s period, the grid voltage is in normal range that the inverter outputs 50kW rated active power with the active current component I_d=I_{Nm}=107A. At the moment of 0.2s, grid rms voltage sudden sags 0.3V_N with the corresponding d-axis component 0.42V_N which is less than 0.47V_N. Thus the active current component I_d keeps unchanged and the VSG issues capacitive reactive power to compensate the voltage drop. At 0.4s, the grid voltage drops further to 0.2V_N, leading the reactive current component I_q to the maximum value that the VSG outputs capacitive output power only. At 0.6s, the grid voltage recovers, and the VSG returns to work in rated state.

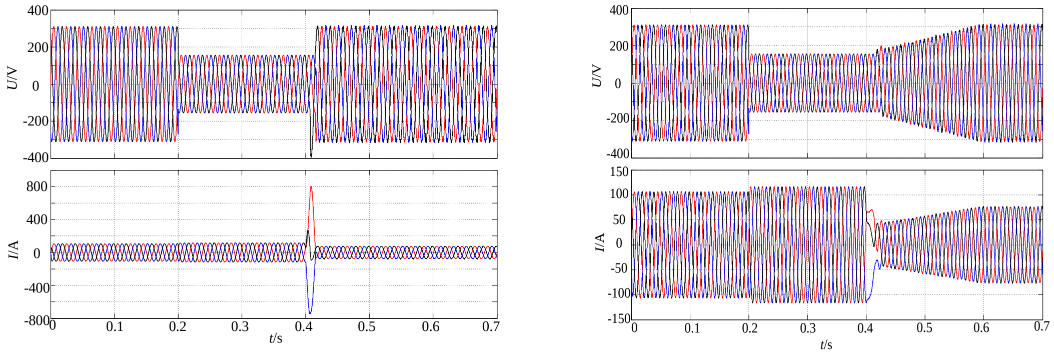




(a). Three-phase inductor current waveform. **(b).** Dq axis inductor current waveforms.

Figure 4. Simulation waveforms of LVRT process.

Figure 5 shows the smooth switching process waveforms when LVRT failure. At 0.2s, the grid voltage drops to 0.5V_N, setting the maximum duration time of 0.2s at this depth of sag, then the VSG will switch to islanding mode after the time of 0.4s since the grid voltage has not restored. Without a smooth switching algorithm shown in Figure 7(a), the moment the contactor opens, the inductor current jumps to eight times the rated value that far beyond the limit. But after the introduction of the smooth switching algorithm, the output voltage keeps unchanged and recovers to the rated value in 0.1s that matches the calculation result. After that, the VSG switches to islanding model and operates stably.



(a). Switch waveforms without a smooth algorithm.

(b). Switch waveforms with a smooth algorithm.

Figure 5. Simulation waveforms of switching process if LVRT failure.

5. Conclusion

This paper designed a LVRT strategy based on VSG control. This strategy can regulate reactive power based on synchronous generator characteristic in accordance with the grid voltage actual value in real time in grid-connected mode without a unique LVRT algorithm to calculate the compensate reactive power instruction. Moreover, considering that the VSG can be controlled as a voltage source, if the depth and duration time of sags beyond the LVRT requirements, this strategy will smooth switch to islanding mode and carry loads independently. Simulations and experimental results have valid that at the transient moments, this strategy will effectively restrict the output current and meet the demands of reactive compensate or voltage recovery.

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