Transient Behavior Analysis of VSG-IIDG During Disturbances Considering the Current Limit Unit

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***Abstract*—The virtual synchronous generator (VSG) is of good prospect for the application of inverter-interfaced distributed generator (IIDG). Similar to conventional synchronous generators, power-angle instability of the VSG-IIDG may occur during faults. However, current studies generally adopt a simplified model and ignore the influence of voltage regulation and current limit in the VSG control. This paper studies the transient behavior mechanism of the VSG-IIDG based on the power-angle characteristics with and without current saturation. The terminal voltage fluctuation of the IIDG due to the voltage regulation of VSG control is also taken into consideration. The typical instabilities and their mechanism are revealed based on different operation conditions. The analysis is verified by simulations based on PSCAD/EMTDC.**

Index Terms--transient behavior analysis, virtual synchronous generator, current limit unit, typical instabilities, inverter-interfaced distributed generator

I. INTRODUCTION

The increasing penetration of distributed generation (DG) brings direct impacts on the stability of the distribution network due to the lack of inertia property. Conventional synchronous generators (SGs) with inherent rotating inertia are capable of injecting the stored kinetic energy under sudden disturbances to operate robustly against instability. Inspired by the concept, the virtual synchronous generator (VSG) control scheme is proposed for inverter-interfaced distribution generators (IIDG). By incorporating the swing equation, the VSG features an inertia property and responses like a SG. The VSG controlled IIDGs (VSG-IIDGs) will inject balancing energy within the proper time scale during disturbances due to the virtual inertia. Besides, the VSG-IIDGs can contribute to the voltage and frequency regulation of the connected distribution network. With the combined advantages of SGs and power electronics, the VSG is playing an important role in the large-scale integration of IIDGs [1].

Since the VSG emulates the behavior of SGs, the operation stability similar to that of conventional SGs will definitely be involved. Reference [2] compares the stability of VSG-IIDGs to the power-angle curve of SGs and proposes a Bang-bang control strategy. Reference [3] investigates how transient energy of VSG-IIDG would be stored and released during disturbances using a Lyapunov function. These studies focus on power-angle stability by analogy. However, the VSG-IIDG model is simplified and cannot accurately reflect the features of inverters.

The VSG control is realized by power electronic devices, hence there are some particularities compared with SGs. The response time of VSG-IIDGs is generally much shorter than that of SGs. The controller is able to adjust the dynamic behaviors of VSG-IIDGs. However, recent studies usually assume that the terminal voltage of the IIDG is constant. The influence of voltage regulation in the transient process is ignored [4].

To avoid damage to power electronic devices, the fault current supplied by the IIDG should be limited, which leads to the nonlinear features and brings challenges to the stability analysis of VSG-IIDGs. Reference [5] analyzes the mechanism of virtual angle stability of droop-controlled IIDGs and points out current saturation leads to complexity of the transient behavior under disturbances. The IIDGs will turn into a current source due to the current limit unit. The analysis assumes the controller turns to instantaneous saturation immediately after disturbances, but the actual instability process is more complex.

This paper analyzes the power-angle stability of the VSG-IIDG considering the saturation of the controller due to the current limit unit. The power-angle characteristics of VSG-IIDG when the controller is in unsaturated and saturated state are presented respectively. The influence of voltage regulation in VSG control is also taken into consideration. Typical instabilities and their mechanism are analyzed based on classifications. Simulations in PSCAD/EMTDC are performed to verify the analysis of the stability mechanism.

II. VSG CONTROL STRUCTURE

The control scheme of the VSG-IIDG is shown in Fig. 1. By controlling the switching pattern of the inverter, the VSG-

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IIDG has the dynamic properties of a SG. The output before filtering reproduces the internal electromotive force of SGs and the output after filtering reproduces the terminal voltage of SGs.

Single SG with an infinite bus is the basis for the analysis of the power system's synchronous stability mechanism with multi-SGs [5]. Motivated by the idea, the system in Fig. 1 is used for the analysis below. Given the fact that the capacity of the IIDG is much smaller than that of the host grid, the host grid is equivalent to an infinite bus.

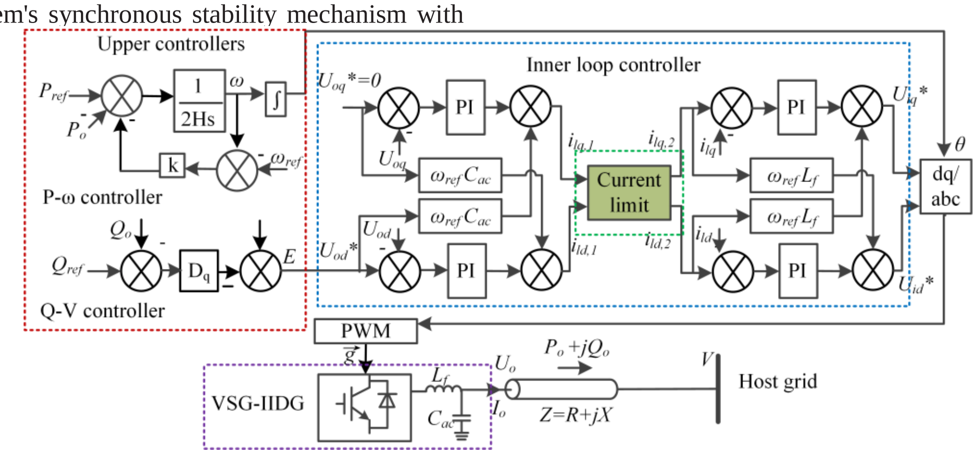


Figure 1. VSG-IIDG control scheme

A. P-ω controller

For SGs, the rotating inertia plays a significant role in terms of stability. However, the output frequency of IIDGs is determined by the control scheme. The P-ω controller implements frequency adjustment in the VSG control [6]. The governing dynamic equations of the P-ω controller is expressed as (1).

$$\begin{cases} 2H\dfrac{d\omega}{dt} = P_{ref} - P_o - k(\omega - \omega_{ref}) \\ \dfrac{d\delta}{dt} = \omega \end{cases} \tag{1}$$

where, P_o is the output active power of the VSG-IIDG, δ and ω are the virtual angle and angular frequency of the VSG-IIDG, P_{ref} and ω_{ref} are the reference of active power and frequency. H and k represent virtual inertia and damping factor respectively.

B. Q-V controller

The Q-V controller serves as a virtual exciter and achieves voltage regulation in the VSG control. It calculates the amplitude of three-phase voltage E according to the active power dispatching instruction Q_{ref}. The droop instruction of Q-V controller is as (2).

$$E - E_{set} = D_Q(Q_{ref} - Q_o) \tag{2}$$

where Q_o is the output reactive power of the VSG-IIDG, D_Q is the droop factor E_{set} is the reference value of the VSG-IIDG terminal voltage.

C. Inner loop controller and current limit unit

The LC filter will reduce the terminal voltage of the inverter slightly, which requires compensation in the control system. Therefore, an inner loop controller is in need. The inner loop controller follows the instruction of the upper controllers (P-ω controller and Q-V controller). A well designed inner loop controller can emulate the characteristics of the synchronous generator accurately and follow upper instructions without steady-state divergence. The responding speed of the inner loop controller is extremely fast and the transient progress of inner loop controller is ignored in the stability analysis of the paper.

To avoid damage to the semiconductors and the disconnection of power suppliers, the output current of an inverter should be safely limited at any instant. An approach to achieve this is to adopt a current limit unit in the inner loop controller. The current limit prevents output from increasing beyond a predetermined value. In general, assume the current limit unit in Fig.1 prioritizes d axis current and the output of the current limit unit is as (3) and (4).

$$i_{lq,2} = \begin{cases} \min[i_{lq,1}, \sqrt{(I_{max})^2 - (i_{ld,1})^2}] & i_{ld,1} \le I_{max} \\ 0 & i_{ld,1} > I_{max} \end{cases} \tag{3}$$

$$i_{ld,2} = \min(i_{ld,1}, I_{max}) \tag{4}$$

where $i_{ld,1}$ and $i_{lq,1}$ are the input of current limit unit, $i_{ld,2}$ and $i_{lq,2}$ are the output.

III. POWER-ANGLE CHARACTERISTICS OF THE VSG-IIDG

A. Without current saturation

Upper controllers will act accurately without current saturation and the output is determined by P-ω controller and Q-V controller. When the VSG-IIDG operates in a steady state, the terminal voltage is on d axis. The virtual angle δ is equal to the output angle θ of the VSG-IIDG. The power of VSG-IIDG without current saturation are as (5) and (6). Here U_o and I_o are the terminal voltage and the output current of the VSG-IIDG respectively.

$$P_{o,unsat} = \mathrm{Re}[\dot{U}_o \dot{I}_o^*] = U_o^2 G - U_o VG\cos\delta + U_o VB\sin\delta \tag{5}$$

$$Q_{o,unsat} = \mathrm{Im}[\dot{U}_o \dot{I}_o^*] = U_o^2 B - U_o VB\cos\delta + U_o VG\sin\delta \tag{6}$$

where $G - jB = 1/(R + jX)$ is the admittance of the line.

Stability analysis of SGs is generally based on the assumption that the generator is represented by a constant electromotive force behind the direct axis transient reactance [7]. Yet the voltage regulation of IIDGs is much quicker and affected by control strategies significantly [8]. As shown in Fig.2, the VSG-IIDG can be regarded as a SG equipped with an exciter of high response.

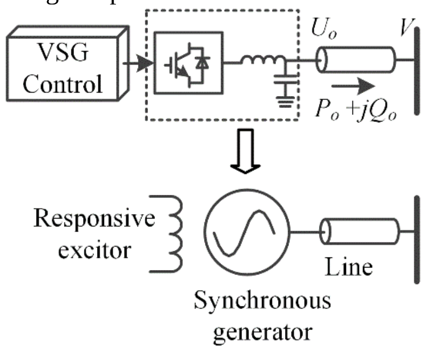


Figure 2. Synchronous generator model

Therefore, according to (2) and (6), the expression of steady-state terminal voltage of VSG-IIDG is as (7). Fig.3 shows that as virtual angle δ varies, the terminal voltage U_o deviates from the reference value to different degrees.

$$U_o = D_Q[Q_{ref} - (U_o^2 B - U_o VB\cos\delta + U_o VG\sin\delta)] + E_{set} \quad (7)$$

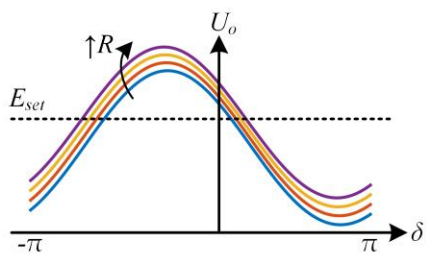


Figure 3. Terminal Voltage fluctuation due to Q-V controller

Substitute (7) to (5) and the power-angle curve without current saturation is shown in Fig.4 as curve Γ_1. The power-angle curve Γ_1 of VSG-IIDG is similar to the power-angle curve Γ_2 with a constant electromotive force E_{set}. Whereas, there is a deviation in the output power since the terminal voltage U_o deviates from the voltage reference E_{set}. The output active power with fluctuated voltage is mostly less than that with constant voltage reference.

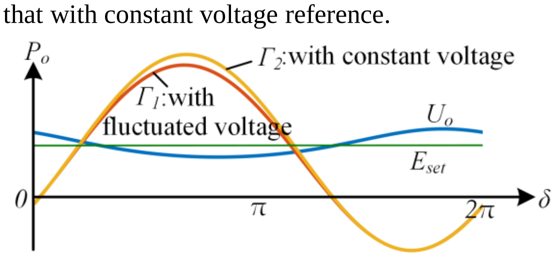


Figure 4. Power-angle curve without current saturation

B. *Considering current saturation*

Once the current limit activates, the output current of VSG-IIDG is identically equal to I_{max}. Then the VSG-IIDG turns into a current source due to the current saturation. The output active power in steady state is:

$$P_{o,sat} = \mathrm{Re}\{[\dot{I}_o(R + jX) + V]\dot{I}_o^*\} \quad (8)$$

Since $\dot{I}_o = I_{max}\angle(\delta - \varphi)$, where φ is the power factor angle of the VSG-IIDG, the output active power with a saturated controller is as (9) and the power-angle curve is shown in Fig.5.

$$P_{o,sat} = I_{max}^2 R + VI_{max}\cos(\delta - \varphi) \quad (9)$$

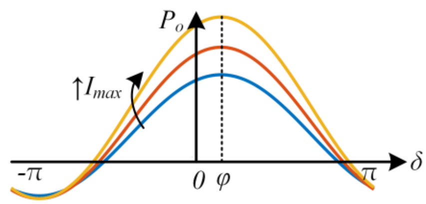


Figure 5. Power-angle curve with current saturation

IV. THE TRANSIENT BEHAVIOR MECHANISM OF IIDG

Consider a sudden voltage drop ΔV of the host grid and the topology of the system remains as Fig.1 under disturbances. Three situations are discussed below. The first is that the current limit unit does not activate during the whole process of disturbance. The second is that the controller is unsaturated when the disturbance occurs, but it turns to saturation after operating for a while. The third is that current saturation happens as soon as the system is subjected to the disturbance.

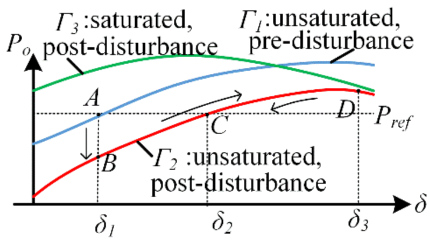
A. *The current limit unit does not activate*

If the current limit unit does not activate during the dynamic process, the operating point goes from point *A* to point *B* immediately after the disturbance as shown in Fig.6. Then the operating point will go along the curve Γ_2 and the virtual angle will increase according to (1). The transient behavior of the VSG-IIDG under such circumstance is just similar to that of SGs. The famous equal-area criterion for stability is applicable. To avoid repetition, it is not described here.

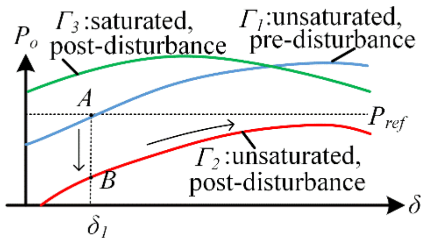
A well-designed VSG control system can achieve strong robustness with rapid response. If each controller of the VSG acts properly and the voltage of the post-disturbance network V_p satisfies condition (10), the operating trajectory will experience damped oscillations due to the damping factor in the P-ω controller. Then the system will reach the equilibrium stable point *C* (Fig.6(a)). If the deceleration area is not able to cover the acceleration area (Fig.6(b)), the virtual angle continues to increase and the system will become unstable.

$$\max(P_{o,sat}) = I_{max}^2 R + V_p I_{max} > P_{ref} \quad (10)$$

The virtual inertia *H* mainly determines the responding speed. The smaller inertia leads to faster response. For example, a small inertia enables a fast recuperation in Fig.6(a) from point *D* to point *C*. Whereas in Fig.6(b) the system will be out of synchronism more rapidly when a small inertia is adopted.



(a) stable



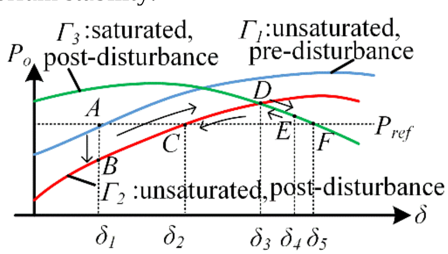
(b) unstable

Figure 6. Transient behavior without current saturation

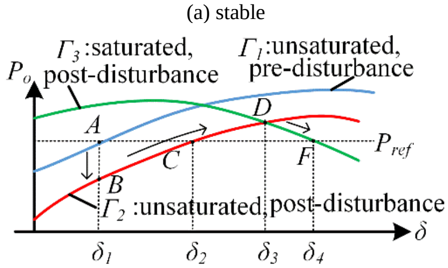
B. *The current limit unit activates during the disturbance*

As shown in Fig.7, the operating point will also go from point *A* to point *B* immediately after the disturbance. Then the operating point will go along the curve Γ_2 and the virtual angle will increase. However, the virtual angular frequency does not reduce to zero when the operating point reaches point *D*, the intersection of the saturated power-angle curve and unsaturated power-angle curve of post-disturbance. Hence the current limit unit is triggered and the operating point will go along Γ_3 instead of Γ_2 .

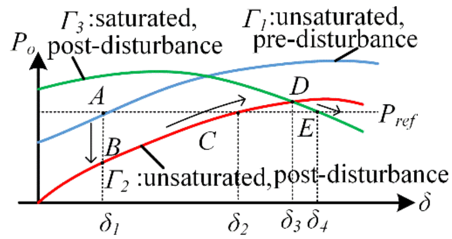
The operating point may reach a stable point *C* if the virtual angular frequency reduces to zero before point *F* (Fig.7(a)). It may also go along Γ_3 continuously if the deceleration area is not able to cover the acceleration area (Fig.7(c)). The system will turn to instability with oscillating output angle. A special occasion is that the virtual angular frequency reduces to zero as soon as it reaches point *F* (Fig.7(b)). The system will then operate at point *F* and reach the equilibrium stability.



(a) stable



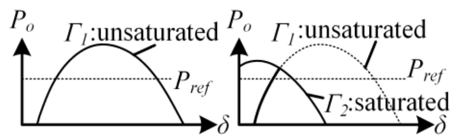
(b) a special occasion



(c) unstable

Figure 7. Transient behavior with current limit unit activating during the disturbance

As stated above, the current limit unit makes the system more prone to instability. Fig. 8 compares the operating curve with and without current saturation. Part of the power-angle curve becomes inaccessible because the output current cannot exceed I_{max} . It means the deceleration area is less likely to cover the acceleration area.



(a) without current saturation (b) with current saturation

Figure 8. Comparison of the operating curve with and without current saturation

C. *Current saturation happens as soon as the system is subjected to the disturbance*

If the controller reaches saturation as soon as the disturbance occurs, the operating point will go from the unsaturated power-angle curve Γ_1 to saturated power-angle curve Γ_2 immediately after the disturbance (Fig.9). It should be pointed out that due to the rapid saturation, the VSG controllers are hardly able to regulate the output accurately. The imprecision of the control system results in inopportune response and continuously rising deviations in output. The system generally tends to instability under such circumstance.

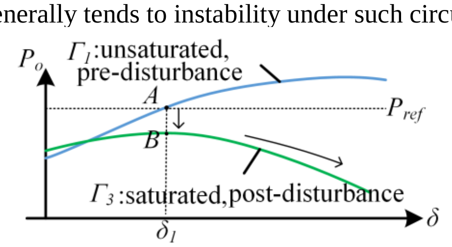


Figure 9. Transient behavior with current saturation once the disturbance happens

V. STUDY CASES

Simulations based on PSCAD/EMTDC are performed to verify the analysis. The topology and control scheme of the VSG-IIDG system is shown in Fig. 1. A voltage drop of the distribution grid occurs at 7.5s.

A. The current limit does not activate

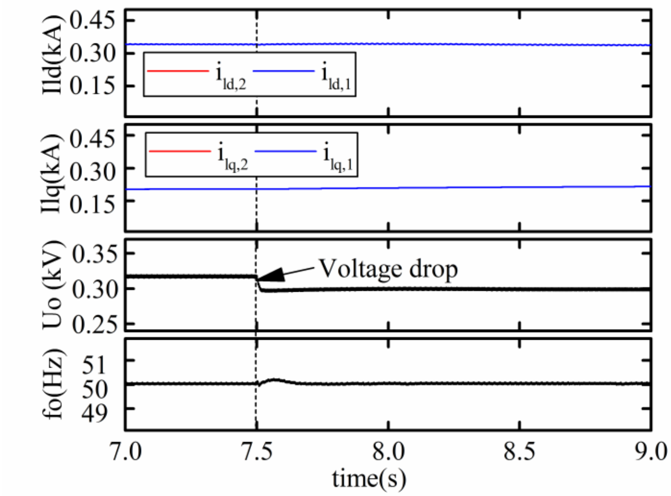


Figure 10. Simulation results when the current limit unit does not activate

When $\Delta V = 15\% V$, $I_{max} = 0.5A$, the system is still stable after voltage drop. The input and output of the current limit unit are the same and current saturation does not happen. The system recuperates after the voltage drop.

B. The controller goes saturated during the disturbance, and the system becomes unstable

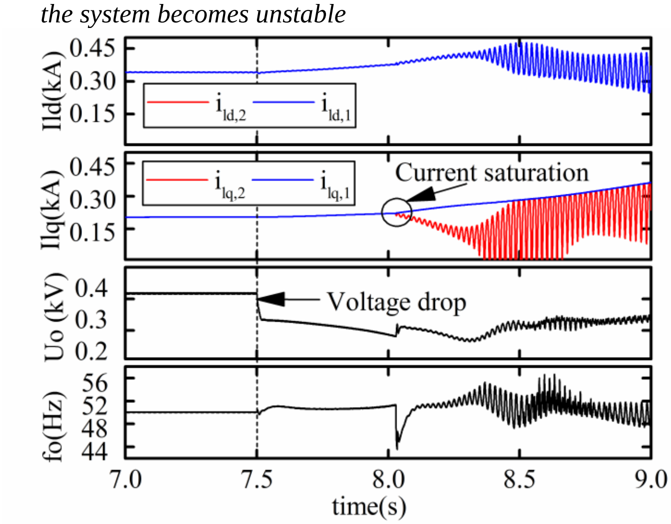


Figure 11. Simulation results when current saturation happens during the disturbance

When $\Delta V = 65\% V$, $I_{max} = 0.5A$, current saturation does not happen as soon as the voltage drops and the input and output of the current limit unit are the same. However, at around 8s, current saturation happens and the system becomes unstable.

C. Current saturation happens as soon as the voltage drops and the system becomes unstable

When $\Delta V = 95\% V$, $I_{max} = 0.4A$, current saturation happens as soon as the voltage drops. The system becomes unstable and the output of the VSG-IIDG is of extreme volatility.

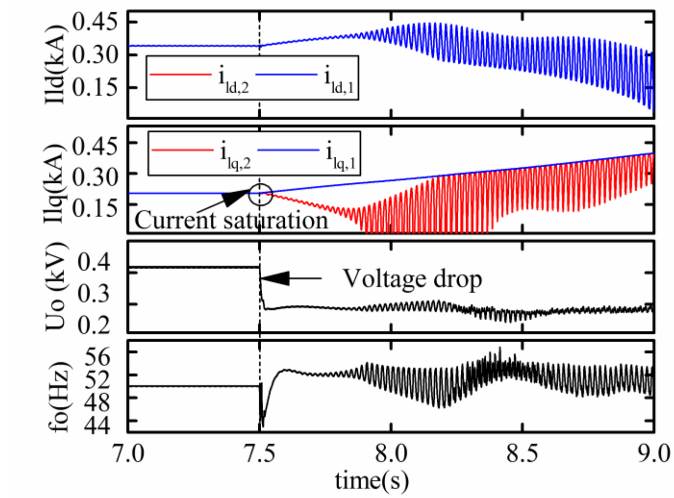


Figure 12. Simulation results when the current saturation happens immediately after the disturbance

VI. Conclusion

This paper studies the transient behavior of the VSG-IIDG during disturbances by analyzing power-angle characteristics with and without current saturation. The analysis shows:

1) The terminal voltage fluctuation of VSG-IIDG due to Q-V controller leads to deviation of the power-angle curve. The output active power with fluctuated voltage is mostly less than that with the constant voltage reference.

2) There are three typical instabilities considering current limit unit. Current saturation results in imprecision of the control system. Part of the power-angle curve also becomes inaccessible due to current saturation. Current saturation makes the system more prone to instability.

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