Adaptive damping control strategy of virtual synchronous generator based on fuzzy control

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Abstract. Based on the topology and small signal model of virtual synchronous generator, the influence of virtual inertia and damping coefficient on transient process is analysed. In order to solve the problem of overshoot with small damping coefficient and slow response with large damping coefficient, a fuzzy control method is introduced, which can completely eliminate overshoot without affecting the response speed. Another fuzzy controller is designed to optimize the output of the virtual synchronous generator in the primary frequency modulation process according to the SOC of the energy storage system.

1. Introduction

New energy generation generally requires frequent changes in power instructions. Every time the power instruction is changed, it is equivalent to experiencing a transient process. The control mode of the inverter determines the impact of changing the power instruction on the grid. Compared with PQ control and PQ droop control, the superiority of VSG grid-connected control mode has been widely recognized. However, if the damping coefficient is too small, it will lead to the phenomenon of oscillation; If the damping coefficient is too large, the response will be too slow and the power requirements cannot be met in time. Fuzzy control can eliminate transient process overtones without affecting the response power command pigment.

Constant damping has major drawbacks. Too large damping can ensure the transient process without oscillation, but will make the output power of primary FM error. Low damping can reduce such errors, but again there are oscillations. In view of this contradiction, many scholars have proposed the methods of transient damping and inertia in recent years. Literature [1] proposed a solution of introducing a transient damping link that reflects the characteristics of the damping windings of synchronous generators, realizing VSG simulation of transient and steady-state characteristics of synchronous generators at the same time, and establishing a small signal dynamic model of VSG control with transient damping characteristics. Li Zhijun et al. The author from Hebei University of Technology proposed a VSG control strategy to improve the damping characteristics of inertia. By adding a differential correction link to the inertia damping control, VSG's inertia damping characteristics in different frequency bands are changed to achieve the purpose of considering the dynamic and static characteristics of the system.

These results solve the contradiction of transient damping and inertia to some extent. However, it relies too much on VSG's small signal model. Due to the linear relationship between the generator power Angle and the output power Pe in a very small range, the accuracy can be guaranteed when the system frequency changes and the power instruction is changed in a small range. However, in the case...
of wind farm custom change or photovoltaic panel illumination mutation, the output power fluctuates greatly, and the small-signal model loses its accuracy.

2. Virtual synchronous generator

2.1. Virtual synchronous generator topology

VSG method is only an improvement on the interface inverter control algorithm, does not need to adjust the grid structure on a large scale, has a strong practical utility in engineering. The structure of the VSG can be roughly divided into two layers, the first layer calculates the active power and reactive power instructions, and the second layer controls the inverter output of the corresponding current or voltage, so that the power output of the inverter meets the requirements of the power command[2]. In this paper, VSG is a current-type virtual synchronous generator, that is, the inverter output current is selected as the control amount, and the control mode is hysteresis control[3].

VSG’s simulation of a real synchronous generator is reflected in the calculation of power instructions. Active power instruction $P_{ref}$ equivalent to the real synchronous generator's primer input power, the inverter output power is equivalent to the real synchronous generator's output power to the external circuit.

In the process of following the change of active power instruction with the active power output of the inverter, a transient module is artificially introduced. This transient module is essentially an equation of the mechanical motion of the rotor:

$$\begin{align*}
J \frac{d\omega}{dt} &= P_m - P_e - D_p(\omega - \omega_0) \\
\frac{d\delta}{dt} &= \omega - \omega_0 \\
\delta &= \int (\omega - \omega_0) dt = \phi - \int \omega_0 dt
\end{align*}$$

In this equation, $\omega$ is system angle frequency, and $\omega_0$ is rated angle frequency; $J$ is the moment of inertia; $D_p$ is the damping coefficient; $P_m$, $P_e$ and $D(\omega - \omega_0)$ respectively represent the corresponding power of mechanical power, electromagnetic power and damping torque. $\delta$ is the internal power angle of the synchronous generator, where $\phi$ is the phase of the port line voltage of the synchronous machine when the phase current is the reference phasor.
From the outside circuit, the inverter output is as if it had a rotational inertia and damping effect. Unlike a real synchronous generator, where the moment of inertia and damping are determined by the mechanical structure and are almost impossible to change after being manufactured, the moment of inertia and damping coefficients of a virtual synchronous machine can be adjusted as required.

In terms of reactive power and voltage amplitude, the synchronous armature resistors are compared to the inverter filter and parasitic resistors[7]. The average voltage of the midpoint of the inverter bridge arm is compared to the excitation motor potential of the synchronizer. In a synchronous generator, the equations that describe the relationship between excitation electromotive force and port voltage are[5]:

$$\dot{E} = \dot{U} + iR_f + jIX_f$$  \hspace{1cm} (2)

In (2), $\dot{E}$ is excitation electric potential, $\dot{U}$ is generator port voltage, $R_f$ and $X_f$ are respectively generator armature resistors and synchronous resistors, $i$ is the stator current.

2.2. Parameters Setting
Convert $J$ and $D_p$ to a per-unit value, introduce variables $H$ and $D$.

$$\begin{cases} 
H = \frac{J_0 \omega_0^2}{S_n} \\
D = \frac{D_0 \omega_0^2}{S_n}
\end{cases}$$  \hspace{1cm} (3)

In (3), $H$ and $D$ are respectively the inertial time constant and damping coefficients after converting to per-unit value, and $S_n$ is rated power capacity.

The most important parameters of a virtual synchronizer are rotational inertia and damping. The rotor mechanical equation can be refined into a second-order small signal system, as shown in Figure 2.

$$SE = \frac{1}{\omega_0^2}$$. $Ps$ $HGs$ $DSPs$ $ss$ $HH$ $\omega_0$ $\omega_0$ $s$ $s$

Figure 2. VSG Small-signal modeling

$S_E$ is the per-unit value of synchronous power, and its expression is:

$$S_E = \frac{1}{S_n} \frac{\partial P^e}{\partial \delta_{\omega_0 \delta}} = \frac{E_m U_e}{S_n Z} \sin(\alpha - \delta_0)$$  \hspace{1cm} (4)

The model is based on two assumptions. At first, we assume that the power instruction $P_m$ is unchanged, and secondly, we assume that the inverter filter impedance is close to pure inductive circuit. In another word, $\alpha \approx 90$ degrees. Write down the meaning of the transfer function between $P_e$ and $P_m$:

$$G_{VSG}(s) = \frac{P_e(s)}{P_m(s)} = \frac{\omega_0 S_E}{H} \frac{1}{s^2 + \frac{D}{H} s + \omega_0 \frac{S_E}{H}}$$  \hspace{1cm} (5)

The natural oscillation angular frequency and damping ratio of this second-order transfer function are:
\[ \omega_n = \sqrt{\frac{S_E}{H}} \]
\[ \xi = 0.5D \left( \frac{1}{\omega_n S_E H} \right) \]

The final virtual synchronous generator parameters are shown in Table 1.

| Parameter                      | Value   |
|--------------------------------|---------|
| Rated active power \( P_n \)   | 5KW     |
| Rated reactive power \( Q_n \)| 0Kvar   |
| Rated frequency \( f_n \)      | 50Hz    |
| Rated line voltage \( U \)     | 380V    |
| Line inductance \( L_f \)      | 0.001H  |
| Parasitic resistance \( R_f \)| 0.004Ω  |
| The inertia time constant \( H \)| 0.1s    |
| Damping coefficient \( D \)    | 15      |
| Primary frequency modulation coefficient \( K_f \) | 10KW/Hz |
| Reactive power regulation factor \( k_q \) | 0.00001 |
| DC side rated voltage \( U_{dc} \) | 1500V   |

3. Fuzzy Control
The Modification of the damping coefficient can be regard as applying two extra components, which can be described as equation:

\[ D = D_0 + \Delta D_1 + \Delta D_2 \]  

In (7), \( D \) is the final damping coefficient of VSG, \( D_0 \) is the initial damping coefficient of VSG, \( \Delta D_1 \) and \( \Delta D_2 \) are the amendment components from transient fuzzy controller and the first frequency modulation fuzzy controller. The value of the first component should make the transient process of power instruction change without overshoot, and the value of the second component is determined by the energy storage unit SOC value.

3.1. Transient Damping Fuzzy control rules
The output of the transient damping fuzzy controller is \( \Delta D_1 \). The control principle of \( \Delta D_1 \) is that the damping coefficient for regulation during the transient process is that the VSG power response is not overstated and zeroed after entering steady state. When the actual power value differs greatly from the power instruction, the VSG damping needs to be reduced appropriately to speed up the response, and when the actual power is closer to the instruction value, the damping becomes larger to suppress overshooting.

The transient damping fuzzy controller has two inputs. The first input is power error \( E \), and the second input is the derivative of power error with respect to time \( E_c \). The expression is as follows:

\[ \begin{align*}
E & = P_{ref} - P \\
E_c & = \frac{dE}{dt}
\end{align*} \]

The fuzzy subset of power error \( E \) is \{NB, NS, O, PS, PB\}, the corresponding language set is \{negative big, negative small, zero, positive small, positive big\}, and the fuzzy domain is [-5, 5]. The
fuzzy subset of derivative of the power error input is \{NB, NS, O, PS, PB\}, the corresponding language set is the same as E. Its fuzzy domain is \([-100,100]\). The fuzzy subset of the VSG damping adjustment is \{NB, NM, NS, O, PS, PM, PB\}, and the fuzzy domain \([-3.5,3.5]\). The Membership degree function is shown in Figure 3.

The design of fuzzy control rules is briefly described here. In the transient process of power instruction change, the ideal situation is that when error E is large, the error change rate is also large, so as to eliminate the error quickly. When the error E is small, the error change rate is also small; As the error E goes to zero, the error rate Ec also goes to zero; There is no overshoot in the whole transient process.

The first step is to eliminate overshoot. The overshooting phenomenon has obvious characteristics, as shown in the case that the error E is already small, the error change rate Ec is still very large, which indicates that the damping is insufficient and the damping should be increased. If the error E is large and the error rate Ec is small, it indicates that the transient response process is slow. This is caused by oversized damping, so damping should be appropriately reduced. Specific fuzzy control rules are shown in Table 2.

| E    | NB | NS | O  | PS | PB |
|------|----|----|----|----|----|
| NB   | PS | PS | NB | NM | PS |
| NS   | PB | PB | O  | O  | PB |
| O    | PB | PS | O  | PM | PB |
| PS   | PB | O  | O  | PB | PB |
| PB   | O  | NS | NM | PS | PS |

3.2. First Frequency modulation Fuzzy control rules
New energy generation is usually equipped with energy storage systems. Generally, the power of new energy itself cannot be adjusted, and energy storage should be combined to participate in a frequency modulation. Therefore, it is necessary to optimize the SOC of energy storage system. The energy storage device used in this paper is battery group, with a total capacity of 5000Ah.

Here are two input variables in the frequency modulation fuzzy controller. The first is the state of charge of the energy storage device, the second input is the frequency offset \(\Delta f\), which is equal to \(f - f_n\).

The variable f is the actual value of power system, and fn is system rated frequency.

The fuzzy subset of battery SOC is \{VL, L, O, H, VH\}, the corresponding language set is \{very low, low, normal, high, very high\}, and the fuzzy domain is \([0,1]\). The fuzzy subset of frequency input is \{L, O, H\}, the corresponding language set is \{below power frequency, normal, above power frequency\}, and the fuzzy domain is \([-1,1]\). The fuzzy subset of the VSG damping adjustment is \{negative large, negative small, zero, positive small, positive big\}, and the fuzzy domain \([-1,1]\). The Membership degree function is shown in Figure 4.
The principle of this fuzzy control is that, if the energy storage device has a high charge, and VSG senses that the frequency of the power grid decreases, then the energy storage system engages in a frequency modulation with multiple discharges, and the damping coefficient $D$ should be increased accordingly. When VSG perceives that the power grid frequency is greater than the rated frequency, the energy storage device reduces or increases the charging amount according to the state of charge to participate in the primary frequency modulation, and correspondingly reduces or increases the damping coefficient $D$.

Based on the above principles, a specific table of fuzzy control rules is developed, as shown in Table 3.

| $P_{ref}$ | The SOC of Energy Storage System |
|-----------|---------------------------------|
| $D$       | $VL$   $L$  $O$  $H$  $VH$      |
| $O$       | $NS$   $NS$ $O$  $PS$  $PB$     |
| $C$       | $O$    $O$  $O$  $PS$  $PB$     |

4. Simulation And Verifications

4.1. Transient damping fuzzy control

The simulation experiment of transient damping fuzzy control is divided into two working conditions. In one case it's a step up, and in the other case it's a down step. It increased from 1KW to 6KW and decreased from 6KW to 1KW.

At $t=0.3s$, change the VSG active power instruction from 1KW to 6KW, and the change range is equivalent to 1.0PN. As can be seen from Figure 5, when the damping is too small, $D=1.5$, the transient process will have overharmonic oscillation. It enters a steady state at $t=1.0$. The damping is slightly
larger. When D=7.5, although there is no oscillation, there is still a slight overshoot, and it enters the steady state at about 0.9s. When D=15 and 20, there is no overharmonic oscillation, but the time to enter the steady state is more delayed at 1.0s and 1.2s respectively.

After the damping of fuzzy control is adopted, the overharmonic oscillation is eliminated and the steady state is entered at t=0.7s. It is proved that the damping fuzzy control strategy is correct and effective.

When the power drops by 5KW, the transient response process is asymmetric even if the damping is the same. This is also the reason for the asymmetry of fuzzy control rules. After fuzzy control, the overshoot can be eliminated and the response can be achieved quickly. In the case of power falling, the transient curves of fuzzy control damping and constant damping are compared in Figure 6.

4.2. First frequency modulation damping control

After introducing fuzzy control, the damping coefficient of VSG that will be a constant without fuzzy control changes with the SOC of the energy storage unit during the period when the frequency is not equal to the active frequency.

Assume that the frequency of the grid decreases by 0.25Hz from the rated frequency during 180s to 360s, and increases by 0.25Hz from the rated frequency during 360s to 540s. The comparison of damping coefficient before and after fuzzy control is shown in fig. 7. During 180s to 540s, the damping coefficient of VSG always fluctuates with the change of SOC. The damping change process is shown in Figure 7.
The initial SOC of the energy storage device is 0.8, the energy is sufficient, according to the first frequency modulation damping fuzzy control rules, the energy storage system appropriately increases the discharge depth, and the first frequency modulation contribution to the system is increased. Therefore, the SOC minimum value has changed from 0.528 to 0.507 after fuzzy control optimization. The comparison before and after SOC optimization is shown in Figure 8.

![Figure 8. SOC comparison before and after optimization.](image)

![Figure 9. Frequency modulation power comparison.](image)

The extra power in the first frequency modulation process before and after optimization is shown in Figure 9. Before the introduction of fuzzy control, if the frequency offset is unchanged, the power change of VSG is unchanged. after the introduction of fuzzy control, the power change is changed with the SOC.

5. Conclusion
In this paper, a transient damping fuzzy controller is designed, so that the damping coefficient is always in a state of adjustment during the transient process of power instruction change, and the following conclusions are obtained:

1. If the fuzzy control rules are appropriate, overshooting can be completely eliminated in the transient process and the speed of entering the steady state is not affected at all, which proves the effectiveness of the control strategy.

2. Based on SOC of energy storage system, another set of appropriate fuzzy control rules is designed to optimize the output of primary frequency modulation of energy storage system in the period when the system frequency is different from the rated frequency.

3. In this paper, the design of fuzzy control rules using heuristic method, more time-consuming and laborious, the follow-up work will focus on the research of general, intelligent fuzzy control rules.

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