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The Generator Excitation Control Based on the Quasi-sliding Mode Pseudo-variable Structure Control

Jian Hu† and Lijun Fu*

Abstract – As an essential means of generator voltage regulation, excitation control plays an important role in controlling the stability of the power system. Therefore, the reasonable design of an excitation controller can help improve the system stability. In order to raise the robustness of the generator exciting system under outside interference and parametric perturbation and eliminate chattering in the sliding mode control, this paper presents a generator excitation control based on the quasi-sliding mode pseudo-variable structure control. A mathematical model of the synchronous generator is established by selecting its power, speed and voltage deviation as state variables. Then, according to the existing conditions of the quasi-sliding mode, a quasi-sliding mode pseudo-variable structure controller is designed, and the parameters of the controller are obtained with the method of pole configuration. Simulations show that compared with the existing methods, the proposed method is not only useful for accurate voltage regulation, but also beneficial to improving the robustness of the system at a time when perturbance happens in the system.

Keywords: Multi-machine power system, Excitation control, Feedback linearization, Quasi-sliding mode, Pseudo-variable structure control, Robustness.

1. Introduction

Excitation control which is one of the main controls of a generator has always been the focus of attention because it plays an important role in regulating the generator voltage and improving the stability of the power system. Excitation control has gradually developed from the early PID control which only involved the generator terminal voltage deviation into the optimal linear control [1], nonlinear excitation control [2-12] and intelligent control [13-15]. However, the linear excitation control taking advantage of linearization near the equilibrium point cannot effectively stabilize the system which is subjected to great disturbance, while the intelligent excitation control which is affected by the conditions of application and the complexity of the algorithm can cause difficulties in practical application. With the development of the nonlinear control theory, the nonlinear excitation control can achieve a better effect and so is widely used in the excitation control of the power system.

The general nonlinear excitation control uses the differential geometry for the feedback linearization of the nonlinear system output state so as to solve the linear problem in the whole defined domain [2]. The power angle deviation is often used as the feedback quantity, but the power angle of the generator is not easy to measure in practical engineering. Based on References [2], References [3,4] use the generator speed deviation instead of its power angle deviation. References [5] proposed a nonlinear adaptive excitation control, which can make the system able to resist disturbance when the system structure parameters change in a certain range. Although these methods are adopted to perform a wide-range asymptotic stabilization of the system, they tend to ignore the accurate terminal voltage regulation required by excitation control. In References [6] an optimal robust excitation control was proposed to improve the static voltage stability of the system when its parameters are uncertain. In References [7] a multi-variable nonlinear excitation control including the state feedback of terminal voltage was introduced to regulate the terminal voltage and improve the system stability. However, when the linear matrix inequality is used to design a robust stabilizing controller, many matrix parameters need to be selected, but there is much difficulty doing so. In References [8] a controller was designed with the generator terminal voltage, active power and rotating speed as a linear combination according to the theory of cooperative control. The controller can not only adjust the terminal voltage accurately but also suppress the oscillation of system power, but it slows down the system response.

Because of its strong robustness in the conditions of parametric perturbation and outside interference, the sliding-mode control has been applied to excitation control in recent years. References [9] proposed an integral sliding mode excitation control method which is used for multi-machine excitation control, in order to suppress the

† Corresponding Author: National Key Laboratory of Science and Technology on Vessel Integrated Power System, Naval University of Engineering, China. (hujian0113@qq.com)
* National Key Laboratory of Science and Technology on Vessel Integrated Power System, Naval University of Engineering, China. (lijunfu2006@sina.cn)
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oscillation and keep the terminal voltage constant. References [10] offered a high-order continuous sliding mode excitation control method to reduce the chattering caused by the sliding mode control. However, no ideal sliding mode control does exist, Whether there is a time delay or a spatial lag in the sliding mode control, the chattering in the sliding mode variable structure control is likely to cause forced oscillations in the system [11].

In order to exploit the advantages of the sliding mode variable structure control and to eliminate the chattering in the sliding mode variable structure control, this paper presents an excitation control based on the quasi - sliding mode pseudo-variable structure control. The main contents of the paper are described in the following sections. Section 2 presents a third-order model of the generator system used in this paper that involves the state variables of its terminal voltage, rotating speed and power. Section 3 refers to the design of a quasi-sliding mode pseudo-variable structure controller according to the system mathematical model and the conditions of quasi-sliding mode, and the use of pole configuration to obtain the parameters of the controller. Section 4 compares method proposed in this paper with the currently mature and widely used linearized power system stabilizer (PSS) excitation control and the commonly-used sliding mode control. Section 5 gives a conclusion.

2. Generator Model

For the synchronous generator, its classical third-order model is expressed as:

$$\begin{aligned}
\dot{\delta}_i &= \omega_i - \omega_0 \\
\dot{\omega}_i &= \frac{\omega_0}{H_i}(P_{mi} - P_{ei}) - \frac{D_i}{H_i}(\omega_i - \omega_0) \\
\dot{E}'_{qi} &= \frac{1}{T'_{d0i}}\left[E_{fi} - E'_{qi} + I_{di}\left(x_{di} - x'_{di}\right)\right]
\end{aligned} \tag{1}$$

The remaining relevant electrical quantities are:

$$U_{tdi} = x_{di} I_{qi} \tag{2}$$

$$U_{tqi} = E'_{qi} - x'_{di} I_{di} = E_{qi} - x_{di} I_{di} \tag{3}$$

$$U_{ti} = \sqrt{U_{tdi}^2 + U_{tqi}^2} \tag{4}$$

$$E'_{qi} = E_{qi} - I_{di}\left(x_{di} - x'_{di}\right) \tag{5}$$

$$P_{ei} = E'_{qi} I_{qi} \tag{6}$$

$$Q_{ei} = E'_{qi} I_{di} \tag{7}$$

$$I_{di} = \sum_{j=1}^{n} E'_{qj}\left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right) \tag{8}$$

$$I_{qi} = \sum_{j=1}^{n} E'_{qj}\left(B_{ij}\sin\delta_{ij} + G_{ij}\cos\delta_{ij}\right) \tag{9}$$

In the equations, the subscript i denotes the i^{th} generator, δ its power angle, ω its rotor angular speed, ω_0 its synchronous angular speed, H its inertia time constant, P_m its mechanical power, P_e its output power of generator, D its damping factor, E'_q the transient potential of q axis, T'_{d0} the time constant of the excitation winding when the stator is in open circuit, E_q the no-load EMF, E_f the control quantity representing excitation voltage, I_d the current of d axis, x_d and x'_d the synchronous reactance and the transient reactance of d axis respectively, and U_t the terminal voltage.

The derivation of the generator output voltage and power is formulated below:

$$\dot{U}_{ti} = \frac{\partial U_{ti}}{\partial \delta_i}\dot{\delta}_i + \frac{\partial U_{ti}}{\partial E'_{qi}}\dot{E}'_{qi} \tag{10}$$

$$\dot{P}_{ei} = \frac{\partial P_{ei}}{\partial \delta_i}\dot{\delta}_i + \frac{\partial P_{ei}}{\partial E'_{qi}}\dot{E}'_{qi} \tag{11}$$

Eqs. (2)~(9) are substituted into Eqs. (10) and (11). Using the theory of direct feedback linearization for linear transformation, it is possible to get a model [12] of the generator with the terminal voltage deviation, output power deviation and speed deviation as state variables, And the load disturbance is taken into account. The formula is:

$$\dot{X}_i = A_i X_i + B_i u_i + D_i d \tag{12}$$

where

$$A_i = \begin{bmatrix} 0 & 0 & -\dfrac{1}{T'_{d0i}} \\ 0 & -\dfrac{D_i}{H_i} & -\dfrac{\omega_{0i}}{H_i} \\ 0 & f_{i1} & -\dfrac{f_{i2}}{T'_{d0i}} \end{bmatrix},\quad B_i = \begin{bmatrix} \dfrac{1}{T'_{d0i}} \\ 0 \\ \dfrac{f_{i2}}{T'_{d0i}} \end{bmatrix},\quad D_i = \begin{bmatrix} \dfrac{P_{ei}}{T'_{d0i}} \\ 0 \\ 0 \end{bmatrix},$$

$-d_{\max} \le d \le d_{\max}$, $X_i = \left[\Delta P_{ei} \quad \Delta\omega_i \quad \Delta U_{ti}\right]^T$,

$$f_{i1} = -\frac{\left(1 + x'_{di}B_{ii}\right)\left(-E'^2_{qi}B_{ii} - Q_i\right)U_{tqi}}{U_{ti}I_{qi}} - \frac{x'_{di}\left(1 + x'_{di}B_{ii}\right)P_{ei}}{U_{ti}},$$

$$f_{i2} = \frac{\left(1 + x'_{di}B_{ii}\right)U_{tqi}}{U_{ti}I_{qi}}$$

3. Quasi-sliding Mode Pseudo-variable Structure Excitation Control

3.1 Design of excitation controller

The control law of the third-order generator model shown in (12) is:

$$u_i = -u_{eqi} - u_{di} \tag{13}$$

where

$$u_{eqi} = v_i = k_{i1}\Delta P_{ei} + k_{i2}\Delta\omega_i + k_{i3}\Delta U_{ti} = KX$$

Here u_{eqi} represents the equivalent quasi-sliding mode control part of the system, the coefficients k_i are selected according to the quasi-sliding mode control law, and u_{di} represents the calibration control of the system, which is corresponding to the pseudo-variable structure control law.

The following equation is derived from (6).

$$\begin{aligned}\dot{P}_{ei} &= \frac{1}{T'_{d0i}}\left(E_{fi} - E_{qi}\right)I_{qi} + E'_{qi}\dot{I}_{qi} \\ &= \beta_i E_{fi} + \alpha_i\end{aligned} \tag{14}$$

where

$$\begin{cases}\alpha_i = \left(U_{tqi} + I_{di}x'_{di}\right)\dot{I}_{qi} - \dfrac{E_{qi}I_{qi}}{T'_{d0i}} \\ \beta_i = \dfrac{I_{qi}}{T'_{d0i}}\end{cases}$$

Then, in regard to the excitation control law, the following equation can be obtained.

$$E_{fi} = \left(u_i - \alpha_i\right)/\beta_i \tag{15}$$

3.2 Control law of quasi-sliding mode pseudo-variable structure

Considering generality, suppose the sliding hyperplane of the quasi-sliding mode control is:

$$s(x) = C_{i1}\Delta P_{ei} + C_{i2}\Delta\omega_i + \Delta U_{ti} = C_i^T X_i \tag{16}$$

Suppose $C_i^T B_i > 0$ and substitute (11) into (10), then

$$\dot{X}_i = \left(A_i - B_i k\right)X + \left(D_i d - B_i u_d\right) \tag{17}$$

Considering the stability, select the Lyapunov function, which is expressed as:

$$V = \frac{1}{2}s^2 \geq 0 \tag{18}$$

The existing condition of the quasi-sliding mode is expressed as:

$$\dot{V} = s\dot{s} = sC_i^T\dot{X}_i < 0 \tag{19}$$

The substitution of (16) and (17) into (19) leads to

$$\begin{aligned}s\dot{s} &= sC_i^T\left[\left(A_i - B_i k_i\right)X_i + \left(D_i d - B_i u_d\right)\right] \\ &= sC_i^T B_i\left\{\left[\left(C_i^T B_i\right)^{-1}C_i^T A_i - k_i\right]X_i + \left[\left(C_i^T B_i\right)^{-1}C_i^T D_i d - u_d\right]\right\} \\ &= sC_i^T B_i\left[\left(\alpha_i - k_i\right)X_i + \left(\beta_i - u_d\right)\right]\end{aligned} \tag{20}$$

where

$$\alpha_i = \left(C_i^T B_i\right)^{-1}C_i^T A_i = \begin{bmatrix} 0 \\ \dfrac{f_{i1}\left(C_{i1}+f_{i2}\right)H_i - T'_{d0i}C_{i2}D_i\left(C_{i1}+f_{i2}\right)}{\left(C_{i1}+f_{i2}\right)H_i} \\ -1 - \dfrac{C_{i2}\omega_0 T'_{d0i}}{\left(C_{i1}+f_{i2}\right)H_i}\end{bmatrix}^T$$

$$\beta_i = \left(C_i^T B_i\right)^{-1}C_i^T D_i d = \frac{dC_{i1}P_{ei}}{\left(C_{i1}+f_{i2}\right)}$$

In order to meet the conditions of the quasi-sliding mode, the following equations are available.

$$\begin{aligned}k_i &= \begin{bmatrix}k_{i1} & k_{i2} & k_{i3}\end{bmatrix} = \alpha_i + \gamma C_i^T B_i C_i^T \\ &= \begin{bmatrix} \dfrac{\gamma C_{i1}\left(C_{i1}+f_{i2}\right)}{T'_{d0i}} \\ \dfrac{f_{i1}\left(C_{i1}+f_{i2}\right)H_i - T'_{d0i}C_{i2}D_i\left(C_{i1}+f_{i2}\right)}{\left(C_{i1}+f_{i2}\right)H_i} + \dfrac{\gamma C_{i2}\left(C_{i1}+f_{i2}\right)}{T'_{d0i}} \\ -1 - \dfrac{C_{i2}\omega_0 T'_{d0i}}{\left(C_{i1}+f_{i2}\right)H_i} + \dfrac{\gamma\left(C_{i1}+f_{i2}\right)}{T'_{d0i}}\end{bmatrix}^T\end{aligned} \tag{21}$$

$$\begin{aligned}u_{di} &= \left(\sup\beta_i + \gamma_d\right)C_i^T B_i s\frac{1}{\lambda} \\ &= \frac{\left[d_{\max}C_{i1}P_{ei} + \left(C_{i1}+f_{i2}\right)\gamma_d\right]\left(C_{i1}\Delta P_{ei} + C_{i2}\Delta\omega_i + \Delta U_{ti}\right)}{\lambda_d T'_{d0i}}\end{aligned} \tag{22}$$

where λ_d, γ, γ_d are design parameters, $\gamma > 0$, $\gamma_d > 0$, and

$$\sup\beta_i = \left(C_i^T B_i\right)^{-1}C_i^T D_i d_{\max}$$

According to (21), the coefficients k_{i1}, k_{i2}, k_{i3} of u_{eqi} can be obtained. Then the substitution of (21) and (22) into (20) can result in:

$$s\dot{s} = -\gamma\left(sC_i^T B_i\right)^2 - sC_i^T B_i\left[\left(\sup\beta_i + \gamma_d\right)C_i^T B_i s\frac{1}{\lambda} - \beta_i\right] \tag{23}$$

In order to satisfy the condition of $s\dot{s} < 0$, the solution can found from the inequality. It is shown as follows:

$$|s| > \frac{\lambda T'_{d0i}U_{ti}I_{qi}}{C_{i1}U_{ti}I_{qi} + \left(1 + x'_{di}B_{ii}\right)U_{tqi}} = \Delta \tag{24}$$

Obviously, when there is interference and if $|s| > \Delta$, the state rail line will automatically enter the sliding mode zone, and move in a quasi-sliding mode. If the max boundary d_{max} of the disturbance d is under estimated, the quasi-sliding mode of the boundary layer can still be maintained. At this point the boundary layer becomes wider and the max boundary of β_i also goes up to $\Delta\sup\beta_i$, which leads to:

$$sC_i^T B_i \geq \lambda\left(1+\frac{\Delta\sup\beta_i}{\sup\beta_i}\right) \tag{25}$$

3.3 System robustness

When a change in parameters of the system component or branch causes an uncertain, Eq. (12) will become:

$$\dot{X}_i = A_i(t)X_i + B_i(t)u_i + D_i(t)d \tag{26}$$

Then the Eq. (20) is rewritten as:

$$\begin{aligned} s\dot{s} &= sC_i^T B_i(t)\left[\left(\alpha_i(t)-k_i\right)X_i + \left(\beta_i - u_d\right)\right] \\ &= sC_i^T B_i(t)\left[\left(\alpha_i(t)-k_i'\right)X_i + \left(C_i^T B_i\right)^{-1} C_i^T D_i d\right] \end{aligned} \tag{27}$$

where

$$k_i' = \alpha_i(t) + \gamma' C_i^T B_i C_i^T \tag{28}$$

$$\gamma' = \gamma + \left(\sup\beta + \gamma_d\right)\frac{1}{\lambda} \tag{29}$$

In the generator system, variation in the component or branch parameters does not deviate from the nominal value much, so the deviation of $\alpha_i(t)$ is not large. As seen from Eq. (27), (28), and (29), when the choice of larger γ and γ_d and smaller λ, makes k_i' large enough, the symbol $s\dot{s}$ will depend on k_i' , while uncertainties of $A_i(t)$, $B_i(t)$ and $D_i(t)$ have little effect on the existence of quasi-sliding mode, Therefore, the system is not only of anti-interference robustness in its quasi-sliding mode control but also of robustness against system parameters perturbation.

3.4 Acquisition of control parameters

The method of pole configuration is used to acquire the control parameters C_i and γ' of the sliding hyperplane $s(x)$=0 of the quasi-sliding mode pseudo-variable structure control. As far as Eq. (26) is concerned, the closed-loop system can be expressed as:

$$\dot{X}_i = \left[A_i - B_i\left(\alpha_i + \gamma' C_i^T B_i C_i^T\right)\right]X_i + D_i d \tag{30}$$

The characteristic value of the closed-loop system is obtained by solving the equation:

$$\begin{aligned} &\det\left\{\lambda I - \left[A_i - B_i\left(\alpha_i + \gamma' C_i^T B_i C_i^T\right)\right]X_i + D_i d\right\} \\ &= \lambda^3 + G_2\left(C_{i1}, C_{i2}, \gamma'\right)\lambda^2 + G_1\left(C_{i1}, C_{i2}, \gamma'\right)\lambda \\ &\quad + G_0\left(C_{i1}, C_{i2}, \gamma'\right) \end{aligned} \tag{31}$$

To configure the three poles of the system, the poles λ_1, λ_2 and λ_3 in the left-hand plane needs selecting

$$\begin{aligned} &\det\left\{\lambda I - \left[A_i - B_i\left(\alpha_i + \gamma' C_i^T B_i C_i^T\right)\right]X_i + D_i d\right\} \\ &= \left(\lambda-\lambda_1\right)\left(\lambda-\lambda_2\right)\left(\lambda-\lambda_3\right) \\ &= \lambda^3 + g_2\lambda^2 + g_1\lambda + g_0 \end{aligned} \tag{32}$$

According to the equality of the corresponding coefficients, the set of equations can be obtained as following:

$$\begin{cases} G_2\left(C_{i1}, C_{i2}, \gamma'\right) = g_2 \\ G_1\left(C_{i1}, C_{i2}, \gamma'\right) = g_1 \\ G_0\left(C_{i1}, C_{i2}, \gamma'\right) = g_0 \end{cases} \tag{33}$$

There are three unknown numbers and three equations in (33), By solving the equations, the control parameters C_i and γ' of the sliding hyperplane $s(x)$=0 can be obtained.

4. Simulation Analysis

In order to verify the quasi-sliding mode pseudo-variable structure excitation control proposed in this paper, the simulation software PSCAD/EMTDC is used to establish a two-machine five-node simulation system, as shown in Fig. 1. The parameters and initial operating points are listed in Table 1 and 2.

This paper compares method proposed in this paper with the currently mature and widely used linearized power system stabilizer (PSS) excitation control and the commonly-used sliding mode control and analyzes the effects of different control methods used in the conditions of suddenly-applied load, three-phase ground fault and

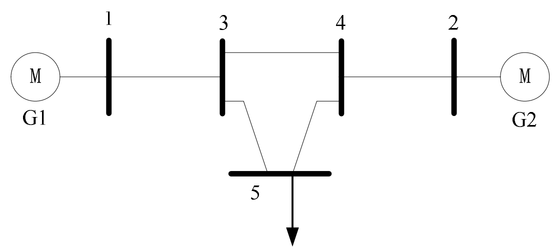

Fig. 1. Power system consisting of two generators with five nodes

Table 1. Parameters of generators

Terms	G1	G2
nominal voltage U (V)	380	380
rated capacity S (MVA)	1.5	1
Armature time constant T_a (sec)	0.023	0.0519
Potier's reactance X_p (p.u.)	0.0998	0.0998
unsaturated reactance X_d (p.u.)	5.44	3.17
Unsaturated transient reactance X'_d (p.u.)	0.192	0.245
Unsaturated transient open circuit time constant T'_{d0} (sec)	2.5154	2.5154
Unsaturated subtransient reactance X''_d (p.u.)	0.108	0.15
Unsaturated supertransient open circuit time constant T''_{d0} (sec)	0.0343	0.0343
unsaturated reactance X_q (p.u.)	4.1	3.17
Unsaturated subtransient reactance X''_q (p.u.)	0.136	0.176
Unsaturated supertransient open circuit time constant T''_{q0} (sec)	0.0343	0.0343
inertia time constant H (sec)	0.6	0.6

Table 2. Initial operating points of generators

G	δ(°)	Ω(p.u.)	E_q(p.u.)	T_m(p.u.)	P(p.u.)	Q(p.u.)
1	34.8	1.02	1.702	0.3289	0.3066	0.2117
2	29.7	1.02	0.993	0.3276	0.3062	0.2412

continuous load change.

The system shown in Fig. 1 is running at the initial operating point. Considering the calculation of the quasi-sliding mode pseudo-variable structure excitation control law with the system parameters, let the damping coefficient of the generator be 0, with B_{ii} of the system ignored. The expression $\lambda_1=\lambda_2=\lambda_3=-2$ is taken as the characteristic value of the closed-loop system to obtain the sliding super-plane coefficient through calculation. For Generator 1,

$$\begin{cases} C_2 = \dfrac{0.332 f_2 h_1 h_2}{2\left(f_2^3 - 0.095 h_1 h_2^2\right)} + \\ \dfrac{\sqrt{0.110 f_2^2 h_1^2 h_2^2 + 4\left(0.237 f_2^2 + 3.6 f_2\right)\left(f_2^3 - 0.095 h_1 h_2^2\right)}}{2\left(f_2^3 - 0.095 h_1 h_2^2\right)} \\ C_1 = h_2 C_2 \\ \gamma' = \dfrac{h_1}{h_2 C_2^2 + f_2 C_2} \end{cases} \tag{34}$$

where

$$\begin{cases} h_1 = 6.323 f_1 - 2.504 f_1 f_2 - 45.45 \\ h_2 = -\dfrac{f_2}{0.033 h_1 \left(f_1 + f_2 - f_1 f_2\right) - 0.005 h_1^2} \end{cases} \tag{35}$$

As a result, the values of coefficients C_{i1}, C_{i2} and γ' as well as k_{i1}, k_{i2} and k_{i3} are only related to the values of f_1 and f_2; that is to say, there is only need to obtain P_e, U_t, U_{tq} and I_{tq} through measurement, and then the parameters of the quasi-sliding mode pseudo-variable structure excitation control can be worked out.

Table 3. Parameters of conventional PSS

Transducer time constant T_6 (sec)	0.00	PSS gain K_S	1.00
Washout time constant T_5 (sec)	10.00	Filter constant A_1	0.00
Filter constant A_2	0.00	1st lead time constant T_1 (sec)	0.00
1st lag time constant T_2 (sec)	6.00	2nd lead time constant T_3 (sec)	0.08
2nd lag time constant T_4 (sec)	0.01	PSS output limit max V_{STMAX} (p.u.)	0.10
PSS output limit min V_{STMIN} (p.u.)	-0.10		

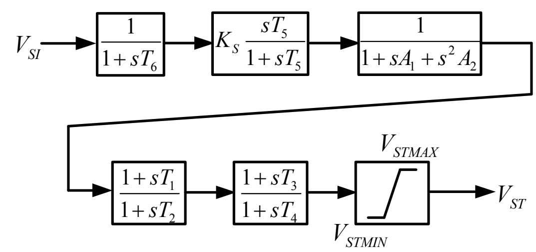

Fig. 2. Block diagram of conventional PSS control structure

In the simulation examples, the proposed control was only applied to G1, but for G2, the linearized power system stabilizer (PSS) excitation control was still used. The conventional PSS control structure in simulation uses the model established according to IEEE Std[16]. Its block diagram is shown as Fig. 2.

T_6 represents a the time constant of the transducer. The gain of the stabilizer is set by the variable K_S and the signal washout is determined according to the time constant T_5. In the next block diagram, A_1 and A_2 represent filter parameters, which are used to deal with some low-frequency effects of the high-frequency torsional filters used in the stabilizers. The next two block diagrams allow two stages of lead-lag compensation, as set by constants T_1 to T_4. V_{STMAX} and V_{STMIN} are the output limitations of the stabilizer. The parameters of the conventional PSS are shown in Table 3.

4.1 Simulation analysis of suddenly applied load

It is found from simulation that at the 25th second, the system load suddenly increases from active power 800kW and reactive power 600kVar to 1.2MW and 900kVar. The generators G1 and G2 are connected in parallel by means of droop control, distributing power in the proportion of three to two. The waveforms of output terminal voltage, rotating speed and power are shown from Fig. 3 to Fig. 5.

It is seen from Fig. 3 to Fig. 5 that when the system has a suddenly-applied load, Both the proposed method and the common sliding mode control can get more accurate value of output terminal voltage than the linearized power

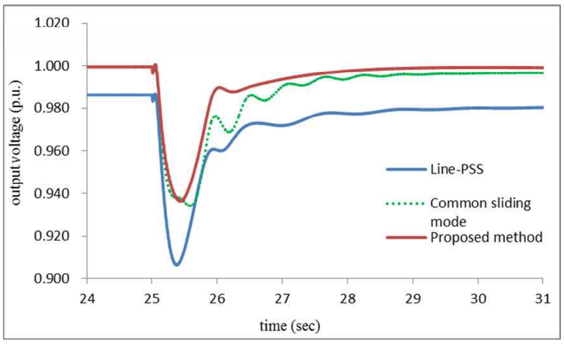

Fig. 3. Output voltage of G1

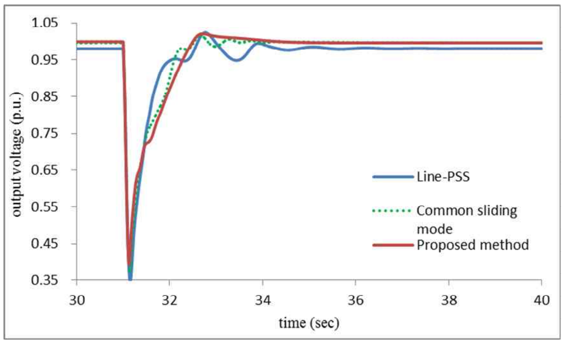

Fig. 6. Output voltage of G1

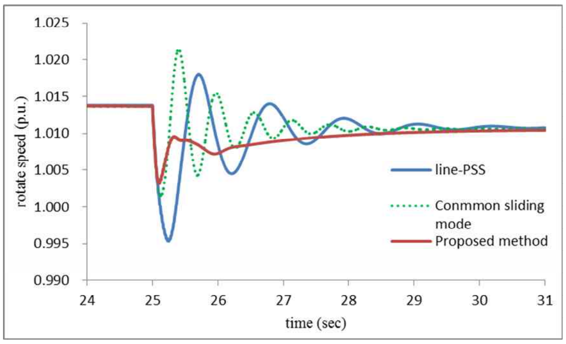

Fig. 4. Rotating speed of G1

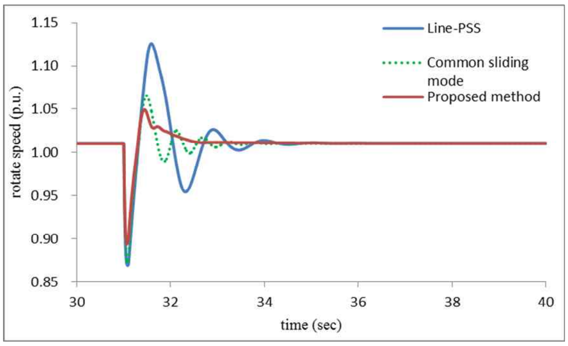

Fig. 7. Rotating speed of G1

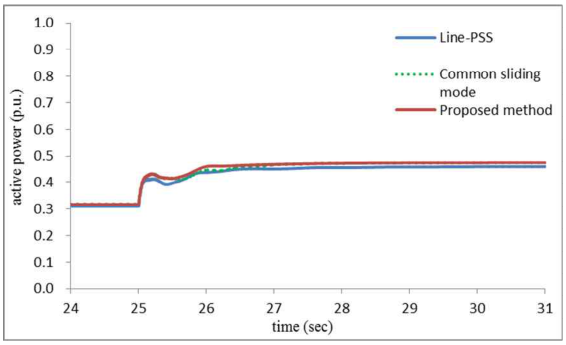

Fig. 5. Output power of G1

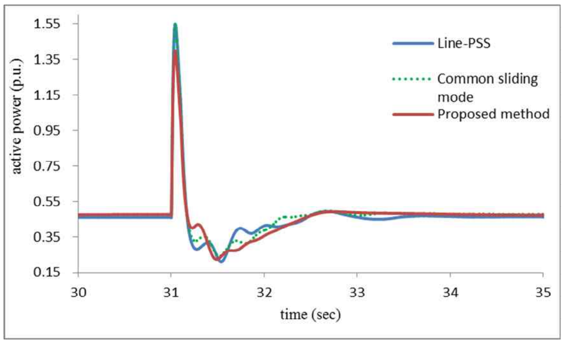

Fig. 8. Output power of G1

system stabilizer (PSS) excitation control. And meanwhile, the proposed method has an advantage over the common sliding mode control and the linear PSS excitation control in obtaining a transient process of generator rotating speed., It shows stronger robustness. There is no obvious difference among the three output power waveforms.

4.2 Simulation analysis of short-circuit fault at generator output terminal

After the application of load to the system, and at the 31th second, the simulation of a three-phase ground short-circuit fault at the generator G1 output terminal, which lasts 0.1 second before being cleared, leads to the waveforms of output terminal voltage, rotating speed and power, as shown form Fig. 6 to Fig. 8.

It is seen from Fig. 6 to Fig. 8 that when a three-phase ground short-circuit fault occurs at the Generator 1 output terminal, a big disturbance will appear in the system., At this time, both the proposed method and the common sliding mode control can get more accurate value of output terminal voltage than the linearized power system stabilizer (PSS) excitation control. And meanwhile, the proposed method, used to get a transient process of the generator rotating speed is superior to the common sliding mode control and the linear PSS excitation control. It shows stronger robustness. There is no obvious difference among the three output power waveforms.

4.3 Simulation analysis of a periodic change of the load

In the simulation, the system has an active load of

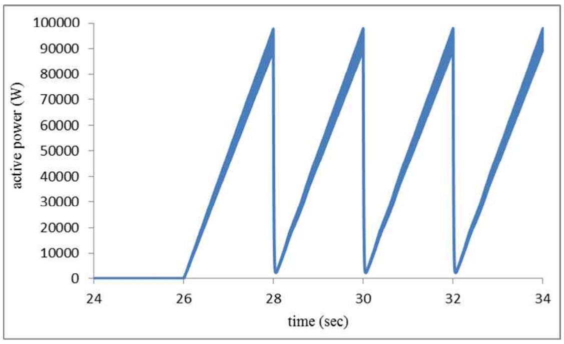

Fig. 9. The load characteristic curve

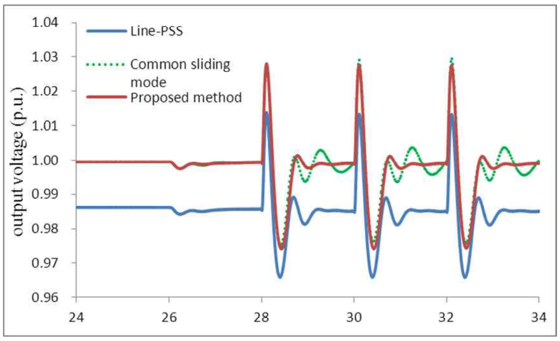

Fig. 10. Output voltage of G1

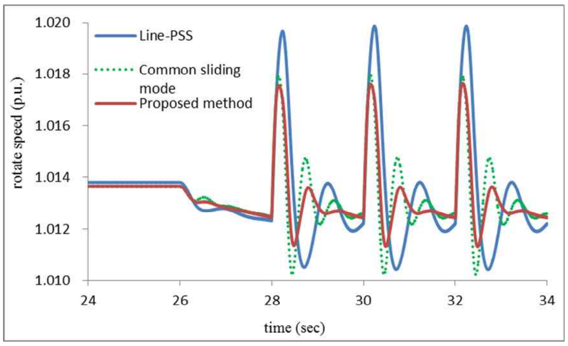

Fig. 11. Rotate speed of G1

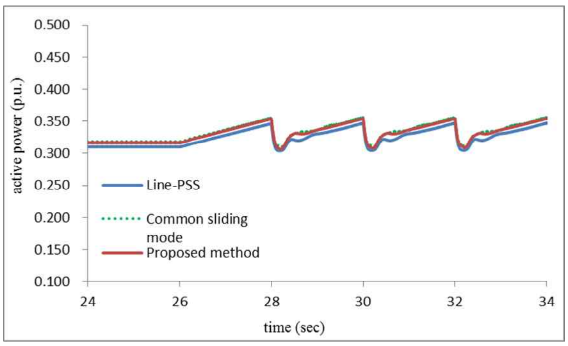

Fig. 12. Output power of G1

800kW and a reactive load of 600kVar in the initial stage, and a load with a continuous periodic change is added at the 26th second. The characteristic curve of the load is

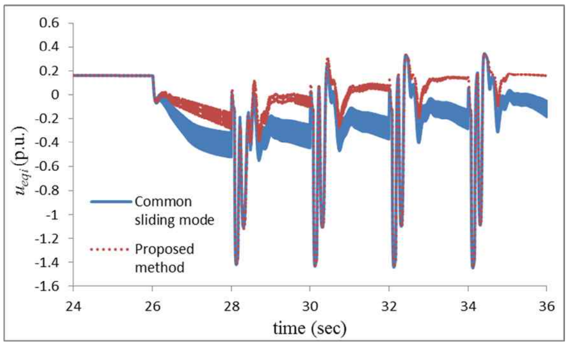

Fig. 13. Variation of u_{eqi} in simulation with a continuously changing load

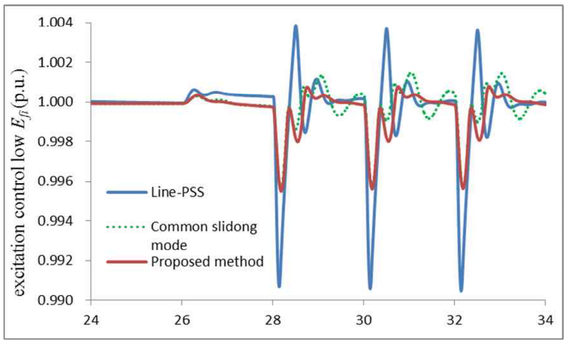

Fig. 14. Variation of E_{fi} in simulation with a continuously changing load

shown in Fig. 9.

The linear PSS control, the common sliding mode control and the excitation control proposed this paper are used respectively to get the waveforms of output terminal voltage, rotating speed and power, as shown from Fig. 10 to Fig. 12.

Fig. 10 shows that both the common sliding mode control and the proposed method are better than the linearization PSS excitation control in the accuracy of voltage regulation, but the common sliding mode control fails to cause the output terminal voltage to go into a steady state. Fig. 11 shows that, when there is a persistent periodic disturbance in the system load, the proposed method can more effectively improve the robustness and dynamic process of the system than the linearization PSS excitation control and common sliding mode control.

In proposed method, u_{eqi} represents the equivalent quasi-sliding mode control part of the system, in the common sliding mode control, u_{eqi} is the equivalent sliding mode control. The curve of u_{eqi} in the common sliding mode controller and proposed method controller is given, as shown Fig. 13.

As seen from Fig. 13, the use of the sliding mode zone by the proposed method instead of the sliding mode surface can eliminate the chattering or weaken it gradually.

The curve of E_{fi} in the line-PSS controller, common sliding mode controller and proposed method controller is given, as shown Fig. 14.

As seen from Fig. 14, the chattering of E_{fi} in the common sliding mode controller is more serious than that in the proposed method controller.

5. Conclusion

In order to improve the stability of the system and the accuracy of output voltage regulation under generator excitation control, this paper proposes a generator excitation control based on the quasi-sliding mode pseudo-variable structure control. This kind of control can be used to accurately regulate the output terminal voltage and meanwhile to improve the transient characteristics of the power system which is subjected to outside disturbance. The proposed method has an advantage over the existing methods in the use of the quasi-sliding mode pseudo-variable structure control to eliminate the chattering of common sliding mode control system and to accurately regulate the generator output voltage. And the system is of strong robustness while it is subjected to parametric perturbation or external interference.

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Jian Hu He received B.S degree in automation from Beijing Institute of Technology in 2012, and the M.S. degree in control science and engineering from Naval University of Engineering in 2014. He is currently pursuing his Ph.D. degree in electrical engineering at Naval University of Engineering, China. His research interests is power system stability analysis and control.

Lijun Fu He received the B.S. degree in electrical engineering from Hunan University of Science and Technology in 1989, and the M.S. and Ph.D. degrees from Wuhan University, China respectively in 1995 and 1997. He is currently employed as Professor at National Key Laboratory of Science and Technology on Vessel Integrated Power System, Naval University of Engineering, China. His research field includes power system design and simulation modeling.