MATEC Web of Conferences 25, 01001 (2015)
DOI: 10.1051/matecconf/20152501001

Switched Reluctance Generator Output Voltage Ripple Reduction Based on Fuzzy Sliding Mode

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ABSTRACT: Aiming at the problem of Switched Reluctance Generator output voltage ripple, this paper designs a fuzzy sliding mode controller based on the analysis of various factors affecting the output voltage ripple. The traditional sliding mode controller has quick convergence, but it has chattering problem. This paper introduces the fuzzy control to select the appropriate sliding mode gain. It can combine with traditional angle control to adjust the output voltage by adjusting the conduction angle. It is more effective in shortening the adjustment time and reducing the overshoot and steady-state of error compared with the classical PID control. Meanwhile, it also solves the chattering problem of traditional sliding mode control. Finally, it makes use of nonlinear model structure to validate that it is effective in restraining voltage ripple and improving the dynamic performance of the system and the voltage quality.

Keywords: switched reluctance generator; sliding mode controller; fuzzy control; voltage ripple

1 INTRODUCTION

The advantages of Switched Reluctance Generator (SRG) such as simple structure, high temperature resistance and suitable for high speed and so on determine it to be the preferred object[2] of the power system applied in fast-growing More Electric Aircraft (MEA) and All Electric Aircraft (AEA) (like F-35). But the output voltage ripple will occur when SRG is in working condition, especially under the interference of sudden addition and subtraction of load or in harsh environment. Therefore, reduction of SRG voltage ripple is the key issue to improve the SRG power quality [3], and it has also become a technical problem SRG awaits to be solved urgently in popularization and application of aviation field.

At present, the researches of domestic and foreign scholars on SRG output voltage ripple reduction are mainly as follows: the optimization design on main power circuit and structure parameters of SRG, the control strategy based on current distribution function [5] and the introduction of intelligent control algorithm to design a feedback controller for optimization [6-8]. In Document [4], the output voltage is conducted optimization control through the design of capacitor filter and voltage feedback regulator, but effects of some harsh conditions on SRG output voltage are not taken into account, and the change of power circuit is bound to bring a certain project difficulty for update and promotion of SRG. In Document [5], the method of current distribution function is proposed for linear SRG to solve voltage ripple, which ignores nonlinear characteristic of SRG in a certain degree. In Document [6], internal mode PI control method is adopted, and it can reduce the output voltage ripple brought by sudden change of speed and load disturbance, but it only regards the output voltage and the phase current as feedback values, not considering effects of other variables on SRG performances, which ignores dynamic characteristics of SRG to some extent.

In this paper, SRG in high voltage DC power supply system of aircraft is regarded as research object, so as to analyze effects of multiple variables on output voltage of SRG. The sliding mode observer is designed based on analysis to output voltage ripple of SRG, which combines with traditional angle control and conducts the phase current compensation through adjustment of flow angle, so that the output voltage ripple can be reduced; meanwhile, the fuzzy control is introduced in the sliding mode observer, the main function of which is to choose suitable sliding mode gain, so that the system can slide around slide mode surface to reduce buffeting that exists in sliding mode variable structure control. Finally, through the integrated nonlinear starter/generator model, simulation tests are conducted for verification. Simulation results show that in case of load voltage, load and speed changes, the introduction of controller will have better control effect on external disturbances of a SRG simulation system, reduce the steady-state error of the output voltage and improve the voltage quality.

2 SRG VOLTAGE RIPPLE ANALYSIS

When SRG is in the stage of self-excited generation

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mode for voltage build-up, the excitation power source will provide initial excitation for the system; when the SRG generates electric energy and provides it capacitor C for charging so as to reach acquired voltage value, the additional external power supply will not be required, and the system will carry out self-excited electric power generation. In self excitation working mode, the motor system is with small weight and high efficiency. But when electric load ripple is larger and capacitor is having charge and discharge, the irregular excitation current in the circuit will be difficult to control; the output voltage ripple will be produced easily; the power generation performance will be affected in a certain degree, and the motor body will also be damaged to some extent. As a result, life of the motor is shortened.

The Formula (1) is a voltage equation in a linear model without the neglect of all power losses:

$$U = L\frac{di}{dt} + iw\frac{dL}{d\theta} + iR_s \tag{1}$$

In this formula, U refers to the output voltage; L refers to the phase inductance; w refers to the angular speed of generator and R_s refers to the phase winding resistance.

If the circumstances such as power loss and winding resistance and so on are taken into account, then in generation stage, the voltage across both ends of the motor winding can be excited in nonlinear model:

$$U = \begin{cases} i_k R_s + \dfrac{d\psi_k(i_k,\theta)}{dt} & \theta_{on} < \theta < \theta_{off} \\ -i_k R_s - \dfrac{d\psi_k(i_k,\theta)}{dt} & \theta_{off} < \theta < 2\theta_{off} - \theta_{on} \end{cases} \tag{2}$$

In this formula, i_k refers to k phase current.

In order to analyze the influence factors of the output voltage ripple more intuitively, the formula [4] of ΔU can be deducted. In power generation stage, it is assumed that the total load is R, voltage across capacitor is U_c, and then in excitation process, the capacitor will not only provide the winding with excitation, but also supply power to the load:

$$C\left(\frac{dU_c}{dt}\right)w = -i_R - i_c \tag{3}$$

In the process of generating continuous flow, capacitor is charged through winding, and the capacitor supplies power to the load:

$$C\left(\frac{dU_c}{dt}\right)w = -i_R - i_z \tag{4}$$

In this formula, i_z, i_c and i_R respectively refer to the armature current, the capacitive current and the load current.

Simultaneously, the Formula (3) and (4) can obtain the capacitor voltage U_c and then obtain the variation ΔU_c of capacitance voltage. While the output voltage variation $\Delta U = \Delta U_c$, and the output voltage variation in the nonlinear model is finally obtained:

$$\Delta U = U_c(\theta_{on})\left(e^{-\frac{30\theta_{off}}{RC\pi n}} - e^{-\frac{30\theta_{on}}{RC\pi n}}\right) - \frac{30P}{C\pi n} \tag{5}$$

In which, n refers to the generator speed; U_c refers to the capacitance voltage; R refers to the total resistance of the load, and P refers to the energy storage in excitation stage.

According to the voltage equations and forms induced from the linear model and the nonlinear model, it can be seen that the parameters affecting output voltage ripple values include voltage U_c, rotational speed n, load R and capacitance C and so on. The load R and rotational speed n are varied with the actual engineering application, and these parameters could have sudden changes in some harsh aviation conditions. Changes of these parameters are bound to cause overshoot of the voltage, generate the voltage ripple and affect the voltage quality.

3 CONTROLLER DESIGN

3.1 *Design idea*

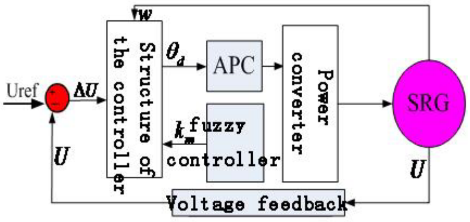

Figure 1. SRG voltage negative feedback controller structure diagram

The controller takes the difference between the reference voltage and the actual feedback voltage as the input variable, while the speed and current are reflected to the controller. The fuzzy sliding mode controller can detect the change signal of state variable of feedback, and compensate the current loop by adjusting the flow angle to achieve the control of the output voltage. That is to say, the sliding mode controller can calculate the input variables and feedback state variables into the angle signal, and combined with angle control to adjust the flow angle θ_d ($\theta_d = \theta_{on} - \theta_{off}$). When $\Delta U = U_{ref} - U < 0$, the output voltage needs to be reduced, and the sliding mode needs to be adjusted appropriately to increase the flow angle; similarly, when it is necessary to increase the output voltage, the sliding mode needs to be adjusted appropriately to reduce the flow angle; use the fuzzy control to select the appropriate sliding mode gain to ensure that the system will run around the sliding mode surface. The voltage negative feedback controller is shown in Figure 1.

3.2 *Sliding mode controller modeling*

SRG model is a working state that can be expressed as follows:

$$\begin{aligned} C\cdot\frac{dU}{dt}&=-\frac{U}{R}+i \\ U&=L\frac{di}{dt}+i\frac{dL}{d\theta}\omega \end{aligned} \tag{6}$$

In which, *U* refers to the output voltage; *R* refers to the total resistance of load; *I* refers to the output current; *w* refers to the angular speed of motor, and *C* refers to the energy storage capacitor, not including the phase winding resistance.

In order to design the sliding mode observer, the definition is made as follows:

$$\begin{cases} x_1 = U_r - U \\ x_2 = -\dot{U} \end{cases} \tag{7}$$

In this formula, U refers to the actual feedback voltage of motor, and U_r refers to the given voltage.

The voltage equation can be expressed in the form of state space:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -a & -b \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ c & d \end{bmatrix}\begin{bmatrix} U_r \\ \omega \end{bmatrix} \tag{8}$$

$$a=1/CL, b=1/CR, c=1/CL, d=-K/CL$$

In which,

$$K=i\frac{dL}{d\theta}$$

The integral sliding mode surface is selected as follows:

$$s=\int_0^t \lambda x_2 + x_1 \tag{9}$$

In which, λ is a constant and greater than zero.

When the system reaches the sliding mode surface, $s=\dot{s}=0$, that is:

$$s=\dot{s}=x_1+\lambda x_2 \tag{10}$$

So $x_2=-x_1/\lambda$, and the formula below can be obtained:

$$x_1 = x_0\exp(-t/\lambda) \tag{11}$$

In this formula, x_0 is the initial value of x_1, and then the constant λ will determine the dynamic response time of the system.

According to the reach-ability of sliding mode motion, when the system moves to the sliding mode surface, it is required to meet the formula as follows:

$$s\dot{s}=s(\lambda x_2+x_1)<0 \tag{12}$$

After analyzing design of the sliding mode control system, the switching line can be taken as follows:

$$H(s,\dot{s}):\dot{s}+\eta s=0 \tag{13}$$

3.3 *Fuzzy sliding mode controller design*

In order to make the system meet higher requirements quickly and stably, the controller requires that when the sliding point of the system is close to the sliding mode surface, it must be both quick and soft. In the sliding mode motion, if the gain of the sliding mode selected is too large, the system will quickly reach the sliding surface, but larger buffeting exists; if the gain of the sliding mode selected is too small, the speed of the system reaching the sliding surface will become slow, but corresponding buffeting will also be reduced. Based on the control law, control is more important, which is usually composed of switching control (force sliding point of the system slide on the sliding mode surface) and equivalent control (keep the system move on the sliding mode surface). The function of fuzzy control is to make the system switch between the equivalent control and the switching control, and the idea of fuzzy control is as follows:

$$\begin{aligned} u&=\frac{\mu_{ZE}(s)\mu_e+\mu_{NZ}(s)(\mu_e+\mu_s)}{\mu_{ZE}(s)+\mu_{NZ}(s)}=\mu_e+\mu_{NZ}(s)\mu_e \\ \mu_{ZE}(s)&+\mu_{NZ}(s)=1 \end{aligned} \tag{14}$$

When the membership function $\mu_{NZ}(s)=1$, $u=\mu_e+\mu_s$, the control law is equivalent of traditional sliding control; when the membership function $\mu_{NZ}(s)\neq 1$, the control law is equivalent of switching control. Motion of the system around the sliding mode surface can be adjusted through changes of the $\mu_{NZ}(s)$, so as to reduce buffeting.

The equivalent control law of the system is as follows:

$$u_e=\frac{1}{C}\cdot\frac{x_1}{\lambda} \tag{15}$$

In which, *C* refers to the energy storage capacitor.

Defined variable is the distance between sliding point and sliding mode surface.

$$d_s=\frac{\dot{s}+\eta s}{\sqrt{1+\eta^2}}$$

Since the system is under various disturbances, the control law for switching control can be taken as follows:

$$u_s=k_m\cdot sign(d_s) \tag{16}$$

In which, the sliding mode gain is chosen according to the inference of a one-dimensional fuzzy controller[9], which is designed to solve the contradiction brought by choice of k_m over too large or too small. The fuzzy controller takes d_s as input, the integer

Table 1. Fuzzy rules

d_s	NB	NM	NS	ZE	PS	PM	PB
k_m	PB	PM	PS	ZE	NS	NM	NB

Table 2. Motor model parameters

Stator pole number	12	Rotor pole number	8
Stator pole arc coefficient	0.5	Rotor pole arc coefficient	0.355
Stator outer diameter	120mm	Rotor outer diameter	69mm
Stator inner diameter	69.8mm	Rotor inner diameter	30mm
Air gap	5.9mm	Number of turns	50
Moment of inertia	0.0013kg·m2	Power	2.2KW

theory domain of the input and output variables is defined as $\{-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6\}$, and adopt gravity center method for defuzzification to output a constant k_m. Specific one-dimensional fuzzy rules are shown in Table 1.

So the control law of the SRG voltage regulating control system is designed as follows:

$$u = u_e + u_s = \frac{1}{C}\cdot\left(\frac{x_1}{\lambda}\right) + k_m \cdot sign\left(d_s\right) \tag{17}$$

According to the analysis based on Lyapunov theorem, corresponding k_m can be found to make the fuzzy sliding mode control system tend to be stable.

The fuzzy sliding mode controller has less fuzzy rules, faster processing speed and certain engineering practice significance.

4 SIMULATION ANALYSIS AND VERIFICATION

In this paper, the three-phase 12/8 nonlinear model built in SIMULINK is used to conduct the simulation test verification. The parameters are shown in the Table 2.

4.1 *Simulation test under changes of load and rotate speed*

According to analysis to the Formula (5), it can be seen that load and rotate speed are the two main external factors that affect voltage change, and it is easy to change suddenly under some special aviation conditions. So in this paper, influences of sudden load change and sudden rotate speed change on output voltage are respectively simulated in the starting/generating integrated nonlinear model of the integrated state feedback controller. Figure 2 shows the changes of output voltage and phase current when suddenly subtracting and respectively adding 50Ω rated load in 0.2s and 0.4s; Figure 3 shows the changes of output voltage and phase current when suddenly subtracting and respectively adding 2000rpm in 0.2s and 0.4s.

It can be seen from the Figure 2 that the overshoot in the build-up process of load voltage is around 2v; when suddenly subtracting load in 0.2s, the controller reduces the phase current by adjusting and increasing the flow angle, the overshoot after increasing voltage is around 1.3v and becomes stable after 0.06s; similarly, when suddenly adding load in 0.4s, the phase current is increased, the overshoot after reducing voltage is around 1.5v and becomes stable after 0.07s. The design of the controller can well stabilize voltage changes in sudden addition and subtraction of load.

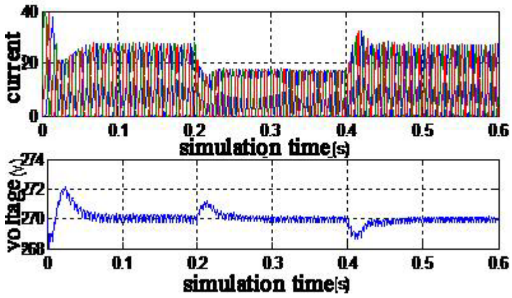

Figure 2. Output voltage and phase current under load changes

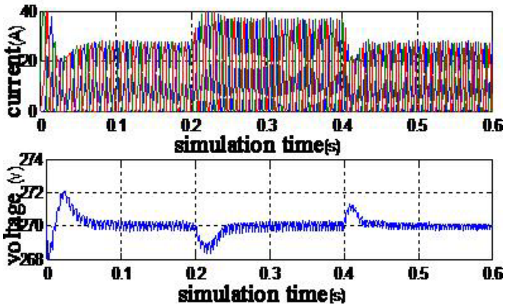

Figure 3. Output voltage and phase current under rotate speed changes

It can be seen from the Figure 3 that when suddenly subtracting rotate speed in 0.2s, the controller will increase the phase current by adjusting and reducing the flow angle, the overshoot after reducing voltage is around 1.8v and becomes stable after 0.08s; similarly, when suddenly adding rotate speed in 0.4s, the phase current is reduced, the overshoot after increasing voltage is around 1.4v and becomes stable after 0.07s. The design of the controller can well stabilize voltage changes in sudden addition and subtraction of rotate speed.

4.2 *Comparison and simulation test of controller*

In the process of voltage build-up and adding/subtracting sudden load, precision of the traditional PID control is not high in the parameters such as overshoot and time adjustment and so on, while the fuzzy sliding mode controller does not have secondary overshoot problem and it shows good performance in speed and convergence, which can improve precision of the SRG control system. In order to better observe the anti-interference effect of the designed controller, we compare the output voltage changes of three controllers when subtracting/adding the same sudden load. The range curves of output voltage and stabilized voltage ripple of the load PID control, the traditional sliding mode control and the fuzzy sliding mode control are respectively shown in Figure 4, Figure 5 and Figure 6.

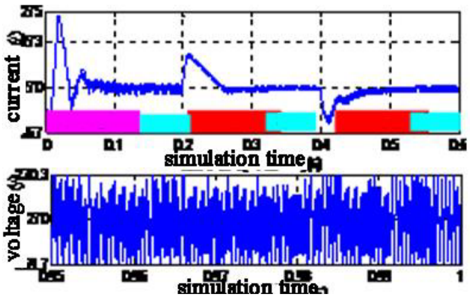

Figure 4. Output voltage and voltage ripple under PID control

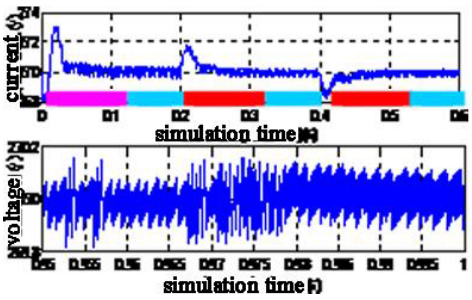

Figure 5. Output voltage and voltage ripple under sliding mode control

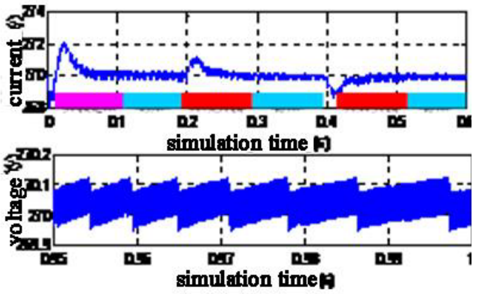

Figure 6. Output voltage and voltage ripple under fuzzy sliding mode control

Control parameter comparisons of the three controllers in the process of voltage build-up and load changes are shown in Table 3.

Table 3. Control parameter comparison of the three controllers

Comparison of three controllers	Voltage build-up process			Subtract load suddenly			Add load suddenly		
	ts(s) Adjustment time	(v) Overshoot value	σ% Overshoot percentage	ts(s) Adjustment time	(v) Overshoot value	σ% Overshoot percentage	ts(s) Adjustment time	(v) Overshoot value	σ% Overshoot percentage
PID control	0.15	5.0	1.85	0.12	2.3	0.852	0.14	2.5	0.926
Sliding mode Control	0.11	2.9	1.074	0.10	1.8	0.667	0.10	1.9	0.704
Fuzzy sliding mode control	0.080	2.0	0.741	0.060	1.3	0.481	0.070	1.5	0.556

It can be seen from the simulation test curve analysis in Figure 4 that the output voltage under the PID controller has secondary overshoot in the process of load voltage build-up and load changes, and the regulation time is relatively long; it can be seen from the simulation test curve analysis in Figure 5 that the output voltage in the traditional sliding mode controller does not have secondary overshoot, but a certain buffeting exists when tending to rated voltage under load disturbances, and changes are not soft; it can be seen from the simulation test curve analysis in Figure 6 that the output voltage under the fuzzy sliding mode controller not only does not have secondary overshoot, but also can tend to the rated voltage smoothly under load disturbances, so as to well stabilize the output voltage.

In order to better observe control effect of the state feedback controller, the simulation time is extended and the local amplification wave of the output voltage for 0.95--1.0s is kept. It can be seen from the Figure 4 that the ripple range of the stable output voltage under the PID control is basically remained at 269.7v--270.3v, the voltage steady-state error is at -0.3v--0.3v, and voltage changes are irregular. It can be seen from the Figure 5 that the ripple range of the stable output voltage under the sliding mode control is basically remained at 269.82v--270.15v, the voltage steady-state error is at -0.18v--0.15v, and a certain buffeting exists in the process of outputting voltage. It can be seen from the Figure 6 that the ripple range of the stable output voltage under the fuzzy sliding mode control is basically remained at 269.93v--270.13v, the voltage steady-state error is at -0.07v--0.13v, and changes are relatively stable. Without any dramatic change, the output voltage is well stabilized, and the voltage quality is improved.

5 CONCLUSION

This paper has mainly analyzed the multiple effects on output voltage of SRG, and proposed the voltage control strategy of the fuzzy sliding mode. Compared with the traditional PID control, it has solved the secondary overshoot of output voltage and the problem of large output voltage ripple when changing load and rotate speed; meanwhile, it can also well avoid the buffeting problem existing in the control method of the traditional sliding mode, and meet the requirements of speediness, stability and small steady-state error, so as to improve the quality of the output voltage.

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