Optimization of Output Voltage of Switched Reluctance Generator Based on Improved Fuzzy Control

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Abstract. This paper takes the output of the switched reluctance generator as the research object and analyzes the main factors affecting the output voltage ripple. In order to optimize the output voltage of the switched reluctance generator at high speed, this paper proposes an angle position control strategy based on improved fuzzy control. When the load changes, the initial value of the turn-on angle of the fuzzy control adjustment is adaptively identified. Adaptive value of turn-off angle input to the system. This method quickly and accurately changes the conduction angle so that the output voltage is optimized. The simulation results show that compared with the fuzzy control, the improved fuzzy control strategy can effectively optimize the output voltage and reduce the voltage ripple.

1. Introduction

The SRG Operate by Reluctance Principle. Compared with other motors, the SRG has the advantages of simple structure, low cost, and high fault tolerance and are also widely used in wind power generation, electric vehicles, and precision machining[1-3]. The SRG become the object of choice for today’s rapidly growing power systems in More Electric Aircraft (MEA), All Electric Aircraft (AEA) (such as F-35)[4]. The quality of the output voltage of a SRG directly affects the performance of the motor. Especially in aviation, changes in motor load have a certain effect on the output voltage. Therefore, it is of great practical significance to study the optimization problem of the output voltage of the SRG.

The SRG have different control strategies at different motor speeds. At high speeds, SRG generally uses angle position control (APC), Controllable parameters have turn-on and turn-off angles. For APC control, researchers conducted extensive research on control methods. The literature [5] proposes the use of a fixed turn-off angle at high speeds, and PI control to optimize the turn-on angle. But PID control can not improve the influence of outside interference on output. The literature [6-7] develops objective functions and constraints, and uses particle swarm optimization and genetic algorithm techniques to determine the optimal turn-on and turn-off angles. The literature [8-9] adopts the method of neural network to optimize the turn-on and turn-off angle of the switched reluctance motor(SRM), but the calculation is complicated and the time is longer. The literature [10] proposed a fuzzy excitation controller to reduce the noise and torque ripple of SRM. The controller is simple in design and can generate appropriate turn-on and turn-off angles based on the speed of the torque error to improve the torque response. The literature [11] proposed an adaptive SRM intelligent controller. This method uses a fuzzy logic controller to control the turn-off angle and uses adaptive neural improved fuzzy inference. In order to maintain the speed of the motor in the SRM under different load
conditions, the literature [12] proposed a new algorithm for the self-tuning of switching parameters of the switched reluctance motor.

In order to solve the problem of output voltage optimization of the SRG at high speed, based on the analysis of output voltage pulsation, an angle control algorithm based on improved fuzzy control is proposed to optimize the output voltage fluctuation caused by load changes.

2. SRG voltage fluctuation analysis

When the SRG is applied to an aircraft, the aircraft requires a small size and light weight, and can simultaneously complete the function of the equipment. In the excitation mode, the external excitation mode requires the excitation of the external power source, and the self-excited method does not require additional equipment and the power generation efficiency meets the requirements, and the efficiency is high. Therefore, this paper chooses the self-excitation method. Assuming the load is a resistive load. To specifically analyze the factors affecting the output voltage, based on the Kirchhoff current law, the output voltage equation is derived based on the literature [13]. Figure 1. is a circuit diagram of the excitation phase and freewheeling power generation phase. C is capacitor. R is resistive load.

![Excitation phase](image1.png) ![Freewheeling power generation phase](image2.png)

**Figure 1.** New inverter topology

Excitation stage:

$$C \frac{dU}{dt} = -i_\ell - i_r$$  \hspace{1cm} (1)

Freewheeling power generation phase:

$$C \frac{dU}{dt} = i_\ell - i_r$$  \hspace{1cm} (2)

The solution to the (1) and (2) equations for the first-order non-odd linear differential equations with constant coefficients is:

Excitation stage:

$$U = (R i_\ell + f)e^{-\frac{1}{RC_\ell}(\theta - \theta_0)} - R i_\ell$$  \hspace{1cm} (3)

Freewheeling power generation phase:

$$U = (-R i_\ell + f)e^{-\frac{1}{RC_\ell}(\theta - \theta_0)} + R i_\ell$$  \hspace{1cm} (4)

The f is a constant.

It can be seen that the parameters affecting the output voltage are speed, load, capacitance, turn-on and turn-off angle. In the process of high-speed operation of the SRG, the capacitance is constant, and the turn-on angle and turn-off angle are the control variables. The load will change due to the actual working conditions, especially in the complex and harsh aviation environment. This change will inevitably cause voltage ripples, affecting voltage quality and motor power generation performance.
When the generator load increases, the power consumption increases, causing the output voltage to drop. In order to eliminate the impact of load changes on the output voltage ripple of the motor, according to formula (3) and formula (4), control increases the conduction angle to ensure the stability of the power and voltage of the output power. Similarly reduce the load.

3. Fuzzy control
In angle position control, changing the size of the conduction angle is essentially an adjustment based on the output feedback information. Fuzzy control can obtain control input based on feedback information, and has good control effect on systems with strong nonlinearity and uncertainty, and it is robust under external interference conditions. Fuzzy control is simple and easy to implement. Therefore, this paper chooses fuzzy control to adjust the conduction angle in APC.

According to the operating principle of the SRG and the analysis of the output voltage ripple factors, the turn-on and turn-off angle all affect the output voltage. However, due to the significant increase of the excitation current in the inductor falling region, the change of the turn-on angle of the phase current waveform is sensitive. When the actual APC is used, the turn-off angle is generally fixed first to adjust the turn-on angle.

For systems that have difficulty building mathematical models, use fuzzy control for control. The control method of fuzzy control is similar to the way people handle problems. Fuzzy controller structure shown in figure 2. The feedback input of the system enters the fuzzy controller and is blurred. The amount of input is converted into a variable that the fuzzy controller can recognize. The fuzzy control rules set in the knowledge base are used to infer the variables input to the fuzzy inference part, and the fuzzy control obtains the control variables. The control variable generates a variable that the system can recognize through a certain rule and outputs the generated variable to the control system.

![Figure 2. Fuzzy controller structure diagram](image)

The schematic diagram of designing the fuzzy controller to control the turn-on angle is shown in figure 3. The output voltage is fed back to the reference voltage, and both the error $e(t) = (U^* - U)$ and error rate of change $de(t)/dt$ are input to the fuzzy controller. Fuzzy controller according to the set fuzzy rules to get the amount of change in PID parameters ($\Delta K_p$, $\Delta K_i$, and $\Delta K_d$). PID control adjusts the turn-on angle to achieve output voltage optimization.

![Figure 3. Fuzzy Controller Schematic](image)
Based on the basic principles of fuzzy control and the actual control of the output voltage of the switched reluctance generator, the fuzzy control is designed in this paper. This paper uses MATLAB's FIS Editor to design the controller and chooses Mamdani type fuzzy reasoning in the fuzzy logic reasoning Mamdani and Sugeno. The input amount of the fuzzy controller is the feedback error $e(t)$ and error change rate $de(t)/dt$, and the output is $\Delta K_p$, $\Delta K_i$, and $\Delta K_d$. The scope and display range of feedback error $e(t)$ and error rate of change $de(t)/dt$ is $[-12, 12]$. According to the characteristics of PID control, the proportional link is to adjust and reduce the deviation immediately when the system has a deviation. Increase the proportional coefficient can improve the speed of adjustment, smaller error. But the proportional coefficient is too large to reduce system stability. The role of the integral link is to eliminate system static errors. Integral coefficient is inversely proportional to the strength of action. The role of the differential link is to reflect the rate of change of the system deviation signal, to be able to meet the trend of deviation change, and to improve the dynamic performance of the system. Increasing the differential coefficient can adjust the system. But too large differential coefficient will lead to weakened system anti-interference ability. Therefore, the scope and display range of the $\Delta K_p$, $\Delta K_i$, and $\Delta K_d$ are $[0, 3]$, $[-3, 0]$ and $[0, 0.0009]$.

Membership functions for input and output select triangle membership functions. The linguistic variables have 7 language values: NB (negative large), NM (negative middle), NS (negative small), ZO (zero), PS (positive small), PM (middle), and PB (positive).

Motor load changes elicit output voltage fluctuations. According to the relationship between the control law of PID and the change of output voltage, formulate fuzzy rules. Taking the proportional coefficient as an example, the input and output variable surface observation chart is shown in figure 4.

![Figure 4. $\Delta K$: Variable Surface View](image-url)

4. Adaptive control
Using fuzzy controller to adjust the turn-on angle of the APC to optimize the output voltage of the SRG can meet certain regulation needs. However, fuzzy control's quantification factor, scale factor, and fuzzy rules cannot change with system changes. This reduces the control effect of the fuzzy control. When designing the fuzzy controller, the role of adding the initial turn-on angle and limit module is to improve the control accuracy. Under different external circumstances, such as changes in the motor load, the SRG requires different turn-on angles, and the turn-on angle adjustment range is relatively large. Therefore, fixing the initial turn-on angle improves the control effect to some extent. However, if you can predict the approximate range of turn-on angle in a certain situation, input it into the fuzzy controller. This turn-on angle is the reference adjustment turn-on angle. This section proposes a self-adaptive method for finding turn-on and turn-off angles, and combines it with fuzzy control to design an improved fuzzy controller for the SRG.

When the output voltage generates an error, the turn-on and turn-off angles are adjusted adaptively by comparing the magnitude of the output error with the reference error. For three-phase 12/8 SRG, the turn-on and turn-off angles vary from 0° to 45°. Fixed turn-off angle is 35°.
The initial value of conduction angle $\theta$ is 15°. Each change is 0.1°. The output voltage setting is 270V. According to the previous analysis of the relationship between the conduction angle and the loading and unloading, we can see that the conduction angle is proportional to the load change and inversely proportional to the voltage change. So, the formula is as follows:

$$\theta(k) = \begin{cases} 
\theta(k-1) + 0.1 & U < 270V \\
\theta(k-1) - 0.1 & U > 270V \\
\theta(k-1) & U = 270V 
\end{cases}$$

(5)

The $\theta(k-1)$ is the leading phase conduction angle. The $\theta(k)$ is the conduction angle at this time. The conduction angle of any one phase is obtained by the adaptive algorithm of the current phase and the previous phase, and the change of the phase conduction angle is completed before the phase begins to work.

Taking the load sudden increase as an example, the simulation verified that the adaptive control finds the effect of the turn-on and turn-off angle. Adjust the opening angle of the simulation map shown in figure 5. When the load suddenly increases at 0.6s and the opening angle is adjusted individually, the angle adjustment is completed at 0.658s. The change of the angle, the frequency of the angle change, and the setting range of the feedback error all affect the speed and accuracy of the adaptive control search angle. The variation of the angle is inversely proportional to the time of finding the angle, and is proportional to the error of the angle; the frequency of the angle change is proportional to the time of finding the angle, and is inversely proportional to the error of the angle; the range of the feedback time is inversely proportional to the time of finding the angle, It is proportional to the error of the angle. Different combinations of the three parameters will be adaptively adjusted.

![Figure 5. Adjust the turn-on angle simulation diagram](image)

The turn-on and turn-off angles are adjusted at the same time as shown in figure 6 and 7. When the load suddenly increases at 0.6s, the angle adjustment is completed at 0.646s. It can be seen that the speed of finding the angle can be increased as compared to adjusting the turn-on angle alone, and adjusting the turn-on angle and the turn-off angle at the same time. The range of angle change is reduced, which is conducive to the adjustment of fuzzy control. Therefore, this section selects the adaptive control of the turn-on angle and the turn-off angle at the same time. The found turn-on angle and turn-off angle are substituted into the fuzzy controller to improve the control accuracy of the fuzzy control.

![Figure 6. Turn-on angle simulation](image)
5. Simulation

This paper uses Ansoft Maxwell14.0 RMxprt software and Maxwell 2D software to establish an Ansoft SRG model and the relationship of flux, angle and current. Change the relational data obtained in Simulink to get inductance, angle and current relationship. At the same time, the relationship between the two groups is introduced into the look-up table module, and a model of the 12/8 switched reluctance power generation system is built accordingly. The excitation mode of the model is self-excitation. High Speed SRG rated output voltage is 270V. Rated speed is 2000r/min. The stator series is 12. The rotor number is 8. Rated power is 2.2kW. Resistive load is R=66Ω. The storage capacitor is C=1000uF. The phase winding internal resistance is r=0.01Ω (Can be ignored). In the case of an initial speed of 2100r/min, This section simulates sudden load and sudden load reduction under fuzzy control and improved fuzzy control.

Sudden load to full-load fuzzy control simulation is shown in figure 8, and improved fuzzy control simulation is shown in figure 9. From the simulation results, it can be seen that under sudden load, the overshoot of fuzzy control is 1.85%, the regulation time is 0.092s, the steady-state voltage ripple is 1.01V; and the overshoot of the improved fuzzy control is 1.41%, The regulation time is 0.084s, and the steady-state voltage ripple is 0.87V.
The simulation of sudden unloading load to half-load fuzzy control is shown in figure 10. The simulation of improved fuzzy control is shown in figure 11. Under sudden load, the overshoot of fuzzy control is 1.44%, the adjustment time is 0.125s, the steady state voltage ripple is 0.65V; and the overshoot of the improved fuzzy control is 1.01%, and the adjustment time is 0.114s. The steady state voltage ripple is 0.51V.

Figure 10. Discharge load fuzzy control voltage simulation diagram

Figure 11. Discharge load improved fuzzy control voltage simulation diagram

6. Conclusions
This paper presents an improved fuzzy control APC strategy for the output voltage optimization of a high speed SRG. Analysis of the main factor affecting the output voltage is the load change. By studying the fuzzy control strategy, an improved fuzzy control strategy is proposed and an improved module control angle position controller is designed. The simulation results show that, in the effect of output voltage optimization, the improved fuzzy control can take into account the rapidity and accuracy, simple and reliable, and easy to implement in the actual system.

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