Comparative Study on Performance of Aeronautical ISG Based on Brushless Synchronous Generator and PMSG

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Abstract. In this paper, the simulation analysis and research on the starting and generating system based on two-stage brushless synchronous motor and permanent magnet synchronous motor are respectively carried out, and the brushless synchronous motor AC/DC mixed excitation scheme is proposed. The starting operation adopts vector control, and the output voltage precision is improved by adjusting the excitation voltage of the exciter. A permanent magnet synchronous motor starting and generating system is constructed, and the control of starting and generating is realized by using vector control based on SVPWM, the results show that the permanent magnet synchronous motor has fast starting speed, good dynamic and static performance, high power supply quality and simple hardware composition, which reduces the complexity of the control system and is convenient for engineering implementation.

1. Introduction
The starting/generating dual function is one of the key technologies of the all-electric aircraft, and the integrated starter/generator in the aviation power supply system is an important part of the system[1-3]. In the current aircraft power system, brushless synchronous motor has been widely used as a generator. Therefore, to achieve starting/generating of equipment changes, a short research cycle and a low cost are important. And there is a precedent for successful application [4]. In recent years, with the development of rare earth permanent magnet material technology and the development of power electronics technology and control theory, permanent magnet synchronous motor has shown unparalleled advantages, such as simple structure, small size, light weight, high power density, good reliability, which is considered as the first choice for the new generation of power supply system[5,6].

In this paper, the model and simulation of the starting and generating system based on two-stage brushless synchronous motor and permanent magnet synchronous motor are respectively carried out. In particular, the dynamic performance of the system is compared and the feasibility of starting and generating of permanent magnet motor is analyzed.

2. Model and simulation of two-stage brushless synchronous motor starting and generating system

2.1. Modeling of two-stage brushless synchronous motor starting and generating system
The starting and generating system principle of two-stage brushless synchronous motor is shown in Fig.1. The exciter and the main generator are both salient pole synchronous generators. The exciter needs large commutation reactance to realize the characteristics of the current amplifier, so the damping winding is not set. Damping winding can improve the power factor of the motor, improve the ability of the motor to withstand asymmetric load, reduce vibration, noise and loss, etc., so the main
generator set damping winding; The main generator is connected to the three-phase load and the inverter respectively when generating electricity and electric operation. The starting operation adopts vector control, and the motor starting control is realized by controlling the inverter through the controller. The engine serves as both the mechanical load and the driver of the permanent magnet synchronous motor.

Fig. 1 Control schematic diagram of two-stage brushless synchronous motor starting and generating system.

Since the main generator should be used for both power generation and electric operation, the power flow direction is just the opposite, and the mathematical model established by the electric and power generation conventions cannot realize the simulation of the whole process of starting/generating, and the fundamental difference between the two is reflected in the difference of the positive and negative signs of variables in the expression of electromagnetic relationship. In this paper, the judgment control module is established to realize the change of motor working state by controlling the corresponding variables.

The basic electromagnetic relationship of the main generator under the d-q coordinate system based on the generator convention is as follows (1)-(4):

Voltage equation:

\[
\begin{bmatrix}
    u_d \\
    u_q \\
    u_{dL} \\
    0 \\
    0
\end{bmatrix} =
\begin{bmatrix}
    -r & 0 & 0 & 0 & 0 \\
    0 & -r & 0 & 0 & 0 \\
    0 & 0 & r_{sl} & 0 & 0 \\
    0 & 0 & 0 & r_{sd} & 0 \\
    0 & 0 & 0 & 0 & r_{qd}
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q \\
    i_{dL} \\
    i_{qL} \\
    0
\end{bmatrix} +
\begin{bmatrix}
    p \psi_d \\
    p \psi_q \\
    p \psi_{dL} \\
    p \psi_{qL} \\
    p \psi_{qL}
\end{bmatrix} +
\begin{bmatrix}
    -\omega \psi_q \\
    \omega \psi_q \\
    0 \\
    0 \\
    0
\end{bmatrix}
\]

(1)

Torque equation:

\[ T_e = p_b (\psi_d i_q - \psi_q i_d) \]  

(2)

Motion equation:

\[ T_e - T_L = J \frac{d\omega_r}{dt} \]  

(3)

Magnetic chain equation:
Where, $p_o$ is the polar logarithm, \( P \) is the differential operator $\frac{d}{dt}$, $\omega$ is the rotor of the electric angular velocity, $\omega_r$ is the rotor of the mechanical angular velocity.

In addition, this paper adopts the AC/DC hybrid excitation scheme [6] to control the output voltage by adjusting the excitation voltage of the exciter.

2.2. Simulation of two-stage brushless synchronous motor starting and generating system

AC/DC hybrid excitation is adopted for starting operation. At the beginning of starting, the rotation speed is lower than 200r/min, and single-phase ac excitation is adopted. The excitation power amplitude is 200V and frequency is 20Hz. Using 141V dc excitation when $n > 200$ r/min, the power generation speed is set as 2000r / min. Fig.2 shows the armature output voltage and current waveforms of the main generator during the dynamic process from starting to generating.

(a) A phase armature current of the main generator

(b) A phase armature voltage of the main generator
A phase armature current during the conversion of the main generator starting to generating

Fig.2 Simulation waveform of two-stage brushless synchronous motor starting/generating dynamic process

3. Modeling and Simulation of Permanent Magnet Synchronous Motor Starting and Generating System

3.1. Modeling of permanent magnet synchronous motor starting and generating system

The integrated starting and generating system structure of permanent magnet synchronous motor is shown in Fig.3. It is composed of engine, permanent magnet synchronous motor, three-phase converter, starting power, electric load and controller. Vector control based on SVPWM is adopted to realize the control of starting and generating, which reduces the complexity of the control system and facilitates the engineering implementation.

In this paper, the ideal motor model is adopted, and the motor convention is also selected for the reference direction of the motor circuit. Thus, the equation of permanent magnet synchronous motor is shown in equation (5) - (8).
In the synchronous rotation coordinate system, the voltage equations of the permanent magnet synchronous motor are:

\[ u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \]  
\[ u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega (L_d i_d + \psi_f) \]  

The electromagnetic torque and mechanical motion equations of the motor are:

\[ T_e = \frac{3}{2} p [ \psi_f i_q + (L_d - L_q) i_d i_q] \]  
\[ T_e - T_L - B \omega_r = J \frac{d\omega_r}{dt} \]  

Where, \( L_d \) and \( L_q \) are the d-axis and q-axis armature inductance, \( R_s \) is armature resistance of one-phase winding, \( \omega \) is the rotor angular velocity, \( p \) is the number of motor poles, \( T_e \) is the electromagnetic torque of the motor, \( T_L \) is the load torque, \( B \) is the damping coefficient, \( J \) is the rotary inertia of the motor, \( \omega_r \) is the mechanical angular velocity of the rotor.

In addition, in order to meet the integrated design, this paper uses the current as the control variable based on the rotor field orientation vector control to achieve the control of the starting and generating process.

3.2. Simulation of permanent magnet synchronous motor starting and generating system

When generating electricity, the motor is driven by aero-engine, making the permanent magnet motor work in variable speed running state. Therefore, the system parameters are given as follows: the starting speed is set as 3510r/min. In the power generation stage, the speed is set as 4000r/min at first, and suddenly changed to 10000r/min at 0.32s with the motor load unchanged. Fig.4 shows the voltage and current waveforms during system operation.

(a) Three-phase current waveform during stable power generation
4. Conclusion

Through theoretical analysis and simulation research, the following conclusions can be obtained:

1) The starting performance of the permanent magnet motor starting and generating system is good. It can be seen from Fig. 2(b) and Fig. 4(b) that the brushless system contains a large number of 5th and 7th harmonics, which causes the starting torque to pulsate greatly, causing motor vibration and loss at the same time. While in the permanent magnet system, there is almost no harmonic content and the motor runs smoothly.

2) The dynamic performance of permanent magnet synchronous motor system is good. As can be seen from Fig. 2(c) and Fig. 4(c), the maximum impulse current of the permanent magnet motor system is 2.5 times of the steady-state operating current in the process of starting and power generation conversion, while the ratio in the brushless system is 5.5. Instantaneous large current will cause damage to the system.

3) Permanent magnet synchronous motor starting and generating system has a simpler structure. Brushless synchronous motor is a multistage system with complex structure. AC and DC excitation require starting power supply and stable output voltage through voltage regulator, which increases the complexity of the system, increases the weight and volume, and leads to high failure rate.

4) The control method of the permanent magnet synchronous motor starting and generating system is simpler. It can complete the aero-engine starting control and the generator output voltage stability through vector control, requiring less hardware equipment and facilitating engineering realization.
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