Sensorless Starting Control of Brushless Synchronous Machine (BSM) For Aircraft

Phinees Ngoy Tshambe¹, Jiadan Wei
¹College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Email: phikal2014@outlook.com

Abstract. In this paper, the sensorless starting control of brushless AC synchronous machine (BSM) for aircraft is studied. Low speed sensorless control technology is the key to accomplish full speed sensorless control. After injected the high frequency voltage with the three-phase AC excitation, the initial rotor position as the response is shown in this paper. On that basis, the sensorless control from starting to low-speed operation is accomplished. The performance of the starting control system is researched using MATLAB simulation software and the feasibility of the proposed scheme is demonstrated by simulation results.

Keywords: brushless synchronous motor, sensorless control, fluctuating high frequency voltage injection method, DC excitation on-off method, vector control.

1. Introduction

In the context of the emerging development of more electric aircraft and an electric aircraft, the integrated technology of start-up/power generation has become the development of aviation power system trend. Start-up/power generation integration technology enables a motor connected to an aeronautical engine to operate for two, enabling both start-up and power generation functions, which can this motor is referred to as an aeronautical start/generator [1]-[2]-[3]. First, the aviation start/generator drags the aviation engine to rotate to a certain speed so that the aeronautical engine enters its own working state, and then the aeronautical engine instead drives the aviation start/generator so that it emits electrical energy to power devices supplied to on-board electrical equipment [4]. The start-up/power generation integration technology removes the traditional starter, effectively simplifies the engine accessories and reduces weight, improved mobility and reliability, is an important technical feature of advanced aircraft power systems [5].

The generator synchronous machine technology is maturing, motor power density is high, and reliability is high and a good choice for aviation generator, widely used in the aeronautical start/power generation system.
Figure 1. BSM three-stage structure.

To accomplish the sensorless starting control, excitation and injection of high-frequency voltage signal are the first keys as shown by [1] [3] and [4]. The main exciter induced voltage that generated by the injected high frequency voltage in the main exciter will be rectified and transferred into the main generator, the high frequency voltage can be shown as response in the main generator windings. Therefore, the calculation of rotor position can be done according to the response high frequency voltage.

Thus, this work is subdivided in 5 sections. Section II treats about the operation principle in start-up mode of BSM, the injected high frequency voltage method is proposed and the BSM sensorless start-up control is studied. The section III is about the estimation of rotor position. In section IV the simulation results are shown and section V, the final one with the conclusion.

2. Operation principle

2.1. Starting mode of BSM

As shown in Figure 1, the three-stage synchronous machine includes four parts: permanent magnet sub-exciter, main excitation, rotating rectifier and main generator; according to the low speed spectrum, in starting mode, the output of the sub exciter is insignificant and the excitation power could not be given, so just the main exciter and main generator in start-up mode are concerned [3].

In start-up mode, Brushless Synchronous Machine needs the combination of rotor position and excitation control to realize the start-up function. By using the traditional dc excitation, it’s complicated for the main exciter to provide the excitation voltage to the main generator because the induced electromotive in the starting mode is very small in the main exciter; Even by using the single AC phase excitation voltage, it’s difficult for the main exciter to provide enough excitation to the main generator. As solution to provide enough excitation to the main generator is to inject into the main exciter three-phase excitation and [4] proposed The Excitation Control Strategy of the Three-Stage Synchronous Machine in the start mode. In the starting process, excitation control and rotor position are necessary to achieve the sensorless start-up control and because of the low ratio and the less bulky sensorless start-up control is improved and makes the BSM more usable as starter. During start-up process the back electromotive force is not detected as well and because of that as solution, the injection of high frequency voltage into the main exciter field, thus by increasing the amplitude of the signals injected, the machine can reach with high accuracy the estimation of rotor position, hence the signal noise ratio could improve and the output torque also will increase. For the injection of high frequency voltage signal, the literature [1] proposed An Integrated Method for Three Phase AC Excitation and High Frequency Voltage Signal Injection for Sensorless Starting of Aircraft Stater/Generator.

2.2. High-frequency voltage injection method
Into the main exciter the high frequency voltage is injected. That high frequency voltage injected in $\alpha$-$\beta$ frame gives:

\[
\begin{align*}
    u_{ah} &= U_h \cos (\omega_h t) \\
    u_{\beta h} &= U_h \sin (\omega_h t)
\end{align*}
\]

(1)

Through rectifier the output AC excitation voltage and the resulting high-frequency signal will be injected in the winding of main generator. Only the AC excitation voltage can switch the mode of the rectifier as its amplitude is far greater than the high frequency voltage injected, thus the response high frequency signal that contain the information of rotor position $\theta$ is expressed like:

\[
\begin{align*}
    u_{hA} &= K_h U_{hf} \cos \left[ (\omega_h - \omega_r) t + \varphi_h \right] \cos \theta \\
    u_{hB} &= K_h U_{hf} \cos \left[ (\omega_h - \omega_r) t + \varphi_h \right] \cos(\theta - 2\pi / 3) \\
    u_{hC} &= K_h U_{hf} \cos \left[ (\omega_h - \omega_r) t + \varphi_h \right] \cos(\theta + 2\pi / 3)
\end{align*}
\]

(2)

$\omega_r$ is the BSM rotor speed and also the main exciter rotor angular frequency, and $\omega_h$ the frequency of the high frequency voltage response and it's proportional with the variation of the speed of rotor because of the nonlinear of the rectifier, $K_h$ is the ratio, $U_{hf}$ is the high frequency voltage amplitude injected, $\varphi_h$ represents the phase angle, $\theta$ is the rotor position.

So, the high frequency voltage in $\alpha$, $\beta$ reference after Clarke can be expressed as:

\[
\begin{align*}
    u_{ah} &= K_h u_{hf} \cos \left[ (\omega_h - \omega_r) t + \varphi_h \right] \cos \theta \\
    u_{\beta h} &= K_h u_{hf} \cos \left[ (\omega_h - \omega_r) t + \varphi_h \right] \sin \theta
\end{align*}
\]

(3)

3. The position estimate of the rotor

Figure 3. proposed the asynchronous demodulation schematic of the response high frequency voltage signal envelope detection, decoding the information of rotor position. The response voltage $u_{ah}$ and $u_{\beta h}$ contain the rotor position information and is extracted from the bandpass filter (BPF), while the lowpass filter (LPF) is employed to extract the low frequency absolute value harmonic signals $|u_{al}|$ and $|u_{\beta l}|$; For the estimation of rotor position, the sinusoidal $u_{al}$ and $u_{\beta l}$ are obtained by using the signal of module restoration. By estimated rotor position, the low frequency signals $u_{al}$ and $u_{\beta l}$ are determined to be positive or negative for the restoration of the low-frequency signal that contained the rotor position information.
Figure 3. Asynchronous demodulation schematic

After passing by the (BPF), the high frequency voltage injected is expressed as:

\[
\frac{u_{at}}{u_{\phi t}} = K (\omega_h - \omega_r) t \cos \theta \\
\frac{u_{\theta l}}{u_{\phi l}} = K (\omega_h - \omega_r) t \sin \theta
\]  \hspace{1cm} (4)

The band-pass filter is used for extraction of the injected high frequency voltage response and the low-pass (LPF) is employed for the extraction of the envelope signal after high frequency voltage injected takes the absolute value. So, the response frequency that contained the information of the rotor position will be restored and shown as:

\[
\frac{u_{at}}{u_{\phi t}} = K \cos \theta \\
\frac{u_{\theta l}}{u_{\phi l}} = K \sin \theta
\]  \hspace{1cm} (5)

In the phase-locked loop the estimation of rotor position angle is possible. However, since the signal restoration module cannot work correctly due to the uncertainty of the initial rotor position, the restored \(u_{at} \), \(u_{\phi l}\) may not correspond to its polar. then, the actual initial rotor position may be \(\hat{\theta} \), \(\pi - \hat{\theta}\), \(\pi + \hat{\theta}\), \(2\pi - \hat{\theta}\). Hence, the estimated initial rotor position \(\hat{\theta}\) can be calibrated according to the initial rotor location identification. Therefore, to calibrate the initial position, it is necessary to determine the sector of rotor in the two-phase stationary coordinate system in accordance with the induced current in the main generator field through excitation settlement.

4. Simulation results

According on the above theoretical MATLAB program study defines the simulation model of BSM sensorless starting control. The parameters of the simulation are shown in Table 1 and 2.

| Parameter                  | Value   |
|----------------------------|---------|
| Rotor winding’s self-inductance (\(L_r/\Omega\)) | 0.1753  |
| Stator and rotor winding mutual inductance (\(L_m/\Omega\)) | 0.1716  |
| Stator winding self-inductance (\(L_s/\Omega\)) | 0.1764  |
| Stator winding’s resistance (\(R_s/\Omega\)) | 4.4     |
| Rotor winding’s resistance (\(R_r/\Omega\)) | 4.1     |
| Pole pairs                  | 3       |
Table 2. Parameters of main generator

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Inductance of d-axis \(\frac{L_d}{H}\)      | 0.075 |
| Inductance of q-axis \(\frac{L_q}{H}\)      | 0.058 |
| Self-inductance of excitation winding \(\frac{L_r}{H}\) | 5.44  |
| Armature winding resistance \(\frac{R_s}{\Omega}\) | 3     |
| Excitation winding resistance \(\frac{R_f}{\Omega}\) | 20    |
| Pole pairs                                     | 1     |

The three phase voltage of the main exciter armature winding is generated by excitation voltage, and it is also sine signal superimposed with high frequency signal as shown in figure 4, thus the two-phase excitation voltage waveforms could be deduced and they are sine and cosine signal superimposed with high frequency signal shown in figure 5. The induced voltage of the armature winding of the main exciter are input into the rotating rectifier, it can be seen from figure 6. that the rotating rectifier output voltage also contains high-frequency voltage signal, which is equivalent to the high frequency signal injected into the main generator windings field, the high frequency response voltage signal with the rotor position information can be extracted from main generator windings generated by the indirectly injected high frequency voltage.

Figure 4. The waveforms of three-phase voltage of the armature winding of the main exciter

Figure 5. The waveforms of two-phase excitation voltage in \(\alpha\beta\) axis

Figure 6. The waveforms of rotating rectifier output voltage

Figure 7. The waveforms of high frequency response voltage signal at zero speed
With the asynchronous demodulation, figure 8. shows the response high-frequency voltages, it will be seen that the amplitude of $u_{\alpha h}$ changes with rotor position, and the envelope curve of the spindle waveform consists of the rotor position. To extract the envelope curve, (LPF) and module absolute value are used to obtain the sinusoidal half-wave $|u_{\alpha l}|$. So, the restoration of the envelope waveforms of $|u_{\alpha l}|$ will be done by estimated rotor position, and the $u_{\alpha l}$ that corresponds to the rotor position will be also done. Therefore, the rotor position could be calculated according to the $u_{\alpha l}$ and $u_{\beta l}$.

Figure 8. The waveforms of response high frequency voltages $u_{\alpha h}$, $|u_{\alpha h}|$, $|u_{\alpha l}|$ (the signal after LPF to $|u_{\alpha h}|$), $u_{\alpha l}$ (the restoration of $|u_{\alpha l}|$)

However, the signal restoration of the envelope waveforms cannot work correctly during initial position calculation, so the estimated initial rotor position may not be inconsistent with the actual position and should be calibrated. Figure 9. and Table 3 shows the relationship between induced currents polarity and sector of rotor, then the estimated initial rotor position can be calibrated according to the sector identification judged by currents polarity as shown in figure 10. The actual rotor position and the angle of estimated rotor are equal in sector I; the estimation of rotor angles can be corrected and at 0.39s harmonized, when in the sector II, III or IV the rotor is located. From the absolute values of $u_{\alpha l}$ and $u_{\beta l}$, the rotor angle estimated is $\theta_{es}=1.14\text{rad}$, and after correction the value is $\pi - \theta_{es}$ matches to sector II, when the rotor position is $2\text{rad}$ in the sector II. While the rotor position is $4\text{rad}$ and $5\text{rad}$ according to the sector III and IV respectively, the rotor angles estimated is $0.86\text{rad}$ and $0.78\text{rad}$, and harmonized to the sectors in the form of $2\pi - \theta_{es}$ and $\pi + \theta_{es}$.

(a) Sector I

(b) Sector II
Figure 9. The two-phase current of the armature winding of the main machine during excitation establishment in different initial positions.

(c) Sector III  
(d) Sector IV

Table 3. Polarity identification

| Sector | Rotor location range | $i_a$ | $i_b$ |
|--------|----------------------|-------|-------|
| I      | $[0, 0.5\pi]$       | $\leq 0$ | $\leq 0$ |
| II     | $[0.5\pi, \pi]$     | $> 0$  | $< 0$ |
| III    | $[\pi, 1.5\pi]$     | $> 0$  | $> 0$ |
| IV     | $[1.5\pi, 2\pi]$    | $\leq 0$ | $> 0$ |

Figure 10. The waveforms of actual position $\theta$ and estimated position $\theta_{es}$ during initial position estimation.

(a) Sector I  
(b) Sector II  
(c) Sector III  
(d) Sector IV
Figure 11 shows the actual and estimated position error waveforms, estimated position at 120rpm the actual position can be tracked well by the estimation position, and the estimated error is always less than 0.2 rad.

Figure 11. The waveforms of estimated position $\theta_{\text{es}}$, actual position $\theta$ and position error $\Delta\theta$ at constant speed.

Figure 12 shows the waveforms in the starting process, the three phase currents and voltages are all sinusoidal, the output torque is constant and the motor speed increases steadily, so the feasibility of the sensorless starting control is verified.

Figure 12. The BSM waveforms in the starting process with proposed sensorless starting control method.

(a) Three-phase current of the armature windings of the main generator  
(b) Three-phase voltage of the armature windings of the main generator  
(c) Speed of the main generator
5. Conclusion
The sensorless starting control of brushless AC synchronous machine in the aircraft is studied in this paper. The AC excitation combined with the high frequency voltage is injected into the main exciter, after rectifying the response high-frequency voltage is shown in the main generator containing actual position $\theta$ information. And the estimation process is shown in this paper. Thus, the result of the simulations of sensorless starting control of brushless AC synchronous machine in the aircraft is accomplished effectively.

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