Simulation of Sensorless Control for the Start-up of Large-Scale Synchronous Condenser Using Static Frequency Converter

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Abstract. In this paper, the structural characteristics of large synchronous condensers and the working principle of static frequency converter are studied firstly. Intermittent commutation and natural commutation are adopted by the inverter on the machine side in low-speed and high-speed stage respectively. Second, methods of sensorless control in different conditions are proposed. The initial rotor position is estimated through two methods, the terminal voltage method and the rotor-flux-oriented method. And similar methods are used in low-speed stage. Besides, phase-locked loop is used in high-speed. Finally, simulation models are established in PSCAD/EMDTC. The rotor-flux-oriented method used in standstill condition and low-speed stage shows better accuracy. And the phase-locked loop is also effective in high-speed stage. Therefore, the sensorless control methods are feasible.

1. Introduction

Large-scale synchronous condenser is an important synchronous machine to produce reactive power in modern high voltage direct current transmission system to enhance system reliability. When overexcited, the synchronous condenser sends reactive power to the grid, and when underexcited, it absorbs reactive power from the grid. Typically, the rotor size is designed small, and the shaft does not extend out of the machine housing for better sealing. Therefore, static frequency converter (SFC) is widely used in the start-up of large-scale synchronous condensers [1, 2].

SFC is the key of the start-up system. Commonly, the start-up process is divided into low-speed stage and high-speed stage by 10% rated speed. Intermittent commutation and natural commutation are adopted by the inverter on the machine side in low-speed and high-speed stage respectively. For commutation, angle of rotor position is required to generate trigger pulses in a certain sequence. Compared to using position sensor, the application of sensorless control reduces costs, thus it has research value. Sensorless control should ensure reliable commutation of the inverter and stability of the system [2-4].
2. Control of SFC

2.1. Basic principle of SFC
The structure of SFC start-up system is shown in figure 1. Generally, the SFC is composed of a rectifier, an inverter and a reactor. Both the rectifier and the inverter are the topology of thyristor bridge, and each thyristor works in a 120° conduction mode. The rectifier converts AC to DC and the inverter converts DC, filtered by the reactor, to variable frequency AC [4, 5].

![Diagram of SFC start-up system]

**Figure 1.** The structure of SFC start-up system

2.2. Low-speed stage
In low-speed stage, some intervals are set to help the inverter commutate effectively. In the intervals, the rectifier works in inverter mode, thus DC-link current $I_d$ is brought down to zero rapidly and the thyristor of the inverter will turn off. This method is called intermittent commutation. The synchronous condenser accelerates till 10% rated speed, and the low-speed stage is finished.

2.3. High-speed stage
In high-speed stage, the inverter uses the terminal voltage to commutate, which is called natural commutation. It is necessary to set an electrical angle leading the phase of natural commutation point and apply trigger pulses at that instant, in order to ensure reliable commutation. Generally the electrical angle $\beta$, called commutation lead angle, is set 60°. Due to the function of speed closed-loop, the synchronous condenser will accelerate to rated speed [4, 5].

3. Sensorless position estimation

3.1. Initial rotor position estimation
In standstill condition, excitation is suddenly added. EMF will be generated but cannot be obtained directly. Commonly the rotor position can be calculated by the terminal voltage.
The first method is called terminal voltage method. If ignore the winding voltage drop, the terminal voltage is equivalent to EMF. By obtaining terminal voltages $u_{ab}$, $u_{bc}$ and $u_{ca}$, initial rotor position is calculated as in equation (1). Terminal voltage method is easy to operate. However, if the change rate of rotor flux is too small, the method would not be feasible [4].

$$\theta_0 = \arctan\left(\frac{\sqrt{3}u_{bc}}{u_{ab} - u_{bc}}\right)$$  \hspace{1cm} (1)

The second method is rotor-flux-oriented method. Principle of this method is shown in figure 2. Terminal voltages $u_{ab}$, $u_{bc}$, $u_{ca}$ and armature currents $i_a$, $i_b$, $i_c$ are transformed to $u_{\alpha}$, $u_{\beta}$ and $i_{\alpha}$, $i_{\beta}$ through Clark transform. Compensate the winding voltage drop, EMF in $\alpha$-$\beta$ coordinate system will be obtained. Then rotor flux is calculated by integration, given in equation (2).

$$\begin{align*}
\psi_{\alpha} &= \int (u_{\alpha} - R_i i_{\alpha}) \, dt \\
\psi_{\beta} &= \int (u_{\beta} - R_i i_{\beta}) \, dt
\end{align*}$$  \hspace{1cm} (2)

Therefore, the initial rotor position angle $\theta_0$ is given with equation (3). Integration calculation can reduce the influence of random errors, thus the method is usually more accurate and reliable [6-8].

$$\theta_0 = \arctan \frac{\psi_{\beta}}{\psi_{\alpha}}$$  \hspace{1cm} (3)

3.2. Rotor position estimation in low-speed stage

EMF in low-speed stage is small, and is interfered by harmonics. It is necessary to filter the terminal voltages $u_{ab}$, $u_{bc}$ and $u_{ca}$, and get filtered voltages $u'_{ab}$, $u'_{bc}$ and $u'_{ca}$. Because the speed is low, armature reaction can be neglected. Then terminal voltage method and rotor-flux-oriented method can be carried out with use of $u'_{ab}$, $u'_{bc}$ and $u'_{ca}$.

3.3. Rotor position estimation in high-speed stage

EMF is large and harmonics is small, thus the waveform is roughly sinusoidal. And the inverter of SFC uses the terminal voltage for commutation rather than EMF. Therefore, the phase angle $\theta_p$ of the terminal voltage is required. Generally, $\theta_p$ leads rotor position angle $\theta$ an electrical angle. The leading electrical angle is load angle $\delta$, caused by armature reaction. In terms of the characteristics mentioned above, phase-locked loop (PLL) is used to obtain $\theta_p$. The basic structure is shown in figure 3.

![Figure 2. Diagram of rotor-flux-oriented method](image)

![Figure 3. Basic structure of PLL](image)

Wherein the PLL transforms terminal voltages $u_{ab}$, $u_{bc}$ and $u_{ca}$ to $u_d$ and $u_q$ by Clark transform and Park transform. Through the effect of close-loop and PI controller, $u_d=0$ when the PLL system is stable, and $\theta'_u$ becomes $\theta_u$. Moreover, the output of PI controller, $\omega'_p$ will be the real speed $\omega$. 
PLL has the advantages of simple structure, rapid response and accurate tracking of phase changes, and anti-interference of the harmonics, thus is widely used [9-11].

4. Simulation of sensorless control in PSCAD/EMDTC

4.1. Simulation of estimation of rotor position

Simulation models are founded in PSCAD/EMDTC. The main circuit of the SFC start-up system is shown in figure 4. Wherein the capacity of the SFC is 4.4MVA and the inductance of the reactor is 2.53mH. For the synchronous condenser, the capacity is 300Mvar, the rated voltage and current are 20kV and 8660A respectively, and the number of pole-pairs is 1. Then the commutation control strategy and the sensorless control methods are carried out according to the description above.

![Figure 4. Simulation models of main circuit in PSCAD/EMDTC](image)

In standstill condition, a time of 30s is set for excitation and estimation of initial rotor position. The simulation results are shown in figure 5 and figure 6. The error produced by terminal voltage method is increasing rapidly after 21s, because the excitation current is tending stable and the change rate of rotor flux is getting smaller. While the error of rotor-flux-oriented method is smaller and more stable.

The simulation results of low-speed stage are shown in figure 7 and figure 8. There are fluctuations of rotor position estimated in terminal voltage method, due to the effect of commutation. While the rotor position estimated in rotor-flux-oriented method is more accurate because the integration calculation weakens the influence of commutation.

As for the simulation in high-speed stage, the terminal voltage phase angle estimated in PLL and real rotor position angle (EMF phase angle) are shown in figure 9. And the phase angle difference between terminal voltage and EMF, together with load angle, are shown in figure 10. Additionally, error between the difference and load angle is shown in figure 11. With the increase of speed, harmonics are becoming smaller, thus angle error is getting smaller.

Min and max value of angle error of each method in different conditions are given in table 1.

| Table 1. Angle error of each method in different conditions (minimum and maximum). |
|---------------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Method                                      | standstill condition          | low-speed stage               | high-speed stage              |
| terminal voltage method                      | -0.45° / 1.96°                | -30.07° / 37.84°              | --                            |
| rotor-flux-oriented method                   | -0.45° / -0.38°               | -0.45° / 6.88°                | --                            |
| PLL                                         | --                            | --                            | -5.05° / 3.11°                |

According to table 1, in both standstill condition and low-speed stage, errors of rotor-flux-oriented method is smaller, thus the method is more effective. Besides, in high-speed stage, the error is also within the angle margin of commutation. Therefore, the estimated angle meets the requirement of commutation in full speed range.
4.2. Start-up simulation

The rotor-flux-oriented method and PLL are used in the start-up simulation of sensorless control. Speed curves of real rotor position and sensorless control are shown in figure 12, and figure 13 presents the speed error of the two control methods. The speed error is caused by the angle error of sensorless estimation. In the switching process from low-speed stage to high-speed stage, the maximum absolute error reaches 25.22rpm. In high speed stage, the error ranges from -18.88 to 7.37rpm. On the whole, the sensorless control brings similar and feasible start-up performance as that using real rotor position.

![Figure 5. Estimated rotor position and real rotor position in standstill condition](image1)

![Figure 6. Angle error of estimated rotor position in standstill condition](image2)

![Figure 7. Estimated rotor position and real rotor position in low-speed stage](image3)

![Figure 8. Angle error of estimated rotor position in low-speed stage](image4)

![Figure 9. Terminal voltage phase and real rotor position in high-speed stage](image5)

![Figure 10. Angle difference and load angle in high-speed stage](image6)

![Figure 11. Error between the angle difference and load angle](image7)
Figure 12. Speed curves of real rotor position and sensorless control

Figure 13. Speed error of the two control methods

5. Conclusions
For the start-up of large-scale synchronous condenser using static frequency converter, related principles are studied firstly, especially the commutation modes. According to the characteristics of different stages of the start-up process, different methods of sensorless control are proposed. The simulation results in PSCAD/EMDTC show that rotor-flux-oriented method is more accurate than terminal voltage method in standstill condition and low-speed stage, and PLL in high-speed stage also shows good performance. The sensorless control brings similar and feasible start-up performance as that using real rotor position. Therefore, the sensorless control methods are effective for start-up of large-scale synchronous condenser using static frequency converter.

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