Research on Control Strategy of STATCOM for Suppressing Subsynchronous Oscillation Based on Nonlinear Method

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Abstract: The dq-axis’ current is flowing into the static synchronous compensator (STATCOM) from the power system and the dq-axis’ current reference value form an error signal. After processing the error signal, a trigger pulse is formed to control the turn-on and turn-off of thyristors in STATCOM. At present, various documents generally adopt PI control to process the error signal. But the coefficient of PI control is difficult to set and the response speed of STATCOM under this control is not very satisfactory. In the paper, a STATCOM control strategy based on nonlinear method is proposed. By introducing feedback controlled quantities \( u_1(t) \) and \( u_2(t) \) into item \( p_{i_1} \) and \( p_{i_2} \) of the STATCOM mathematical model after dq transformation, the aim is to actively control the AC and DC axis current components of STATCOM input system. Based on the principle of nonlinearity, a set of multi-input and multi-output objective functions \( J_1 \) and \( J_2 \) are found. The dynamic and static performance of the control target is dynamically tracked and constrained by the secondary performance index, thus a closed-loop control system is formed which can quickly reflect the varying reactive power of the system. Finally, PSCAD/EMTDC electromagnetic transient simulation software is used to verify the effectiveness of the STATCOM nonlinear control method of Suppressing subsynchronous oscillation in power system.

1. Introduction

As a new flexible device, the static synchronous compensator[1](STATCOM) has the advantages of flexibility and speed. It is mostly used to suppress sub-synchronous oscillation in power systems [2]. How to control STATCOM reasonably and effectively has become a work with theoretical research value and practical engineering significance [3]. Literatures [4] and [5] proposed various improved PI control types related to STATCOM. Although they have better control effects, the disadvantages of PI control still exist. Literature [6] proposed to design an excitation controller based on SCCC and cooperate with classical linear optimal theory to suppress sub-synchronous oscillation. Reference [7] uses the MINC method, by selecting the output function as a linear combination of the state quantities of the non-linear system, and then using the linearization method can effectively suppress sub-synchronous oscillation. This paper proposes a STATCOM control strategy based on a nonlinear method, which is verified by PSCAD / EMTDC electromagnetic transient simulation software, which proves that the control strategy has an excellent suppression effect on sub-synchronous oscillation in power systems.
2. Mathematical model of STATCOM
The static synchronous compensator is a self-commutated bridge circuit composed of high-power electronic devices that can be turned off. Its internal topology [8] is shown in Figure 1:

![Figure 1. The internal topology of STATCOM](image)

The mathematical model [8] of STATCOM in the dq coordinate system is as follows:

\[
\begin{bmatrix}
    p_i_d \\
p_i_q \\
p_u_d \\
p_u_q \\
\end{bmatrix} = 
\begin{bmatrix}
    -R/L & \omega & -\sqrt{3}K \sin \delta \\
    -\omega & -R/L & -\sqrt{3}K \cos \delta \\
    \sqrt{3}K \sin \delta & \sqrt{3}K \cos \delta & 0 \\
\end{bmatrix} \begin{bmatrix}
i_d \\
i_q \\
u_d \\
\end{bmatrix} + \frac{1}{L} \begin{bmatrix}0 \\
0 \\
\end{bmatrix} \sqrt{3}U_r
\]

Among them, \( p = d/dt \) is the differential operator; \( R \) is the equivalent resistance of the switching device in STATCOM; \( L \) is the equivalent inductance of the transformer connecting STATCOM and the system; \( K \) is the proportionality coefficient; \( \omega \) is the synchronization angular frequency; \( \delta \) is the clamp between the STATCOM output voltage and the system voltage at the synchronization signal sampling point Angle; \( U_r \) is the system voltage.

3. Design and working principle of STATCOM nonlinear control
A non-linear differential dynamic system, if the vector field of the system can be controlled by a control input from the outside, the non-linear differential dynamic system is said to be a non-linear control system. The control amount here can be an input energy source, a signal source, etc. Generally, the control amount changes with time. Multiple Input and Multiple Output (MIMO) affine nonlinear control system [9-10] has the following form:

\[
\begin{align*}
    \dot{x}(t) &= f(x) + g_1(x)u_1 + \cdots + g_n(x)u_n \\
    y_1(t) &= h_1(x) \\
        &\quad \cdots \\
    y_n(t) &= h_n(x)
\end{align*}
\]

In the above formula: \( x \in R^n \) is the state vector, \( f(x) = [f_1(x)\cdots f_n(x)]^T \in R^n \) and \( g_j(x) = [g_{1j}(x)\cdots g_{nj}(x)]^T \in R^n \); \( f(x) \) and \( g(x) \) is \( n \)-dimensional smooth vector field; \( u_1 \cdots u_m \) is the control scalar and \( y_1 \cdots y_m \) is the output scalar, and \( h_1 \cdots h_m \) is the output function.

STATCOM output voltage on the dq axis has the following relationship with the access point system voltage:
\begin{align}
\begin{cases}
    u_{sd} = u_{sd} - Lp_{d} + \omega Li_q \\
    u_{sq} = u_{sq} - Lp_{q} - \omega Li_d
\end{cases}
\end{align}

Where: $u_{sd}$ and $u_{sq}$ are the d and q-axis components of the STATCOM access point system voltage, $u_{d}$ and $u_{q}$ are the d and q axis components of the STATCOM output voltage, $i_{d}$ and $i_{q}$ are the d and q axis current components of the system flowing into STATCOM, $\omega$ is the system synchronization angular frequency, $L$ is the equivalent inductance of the transformer connecting STATCOM to the system.

Under PI control, the following relationships exist:

\begin{align}
\begin{cases}
    p_{i_d} = \frac{1}{L}(k_{p1}\Delta i_d + k_{i1}\int \Delta i_d dt) \\
    p_{i_q} = \frac{1}{L}(k_{p2}\Delta i_q + k_{i2}\int \Delta i_q dt)
\end{cases}
\end{align}

Where: $\Delta i_d$ and $\Delta i_q$ are error signals, and $\Delta i_d = i_d - i_{d\_ref}$, $\Delta i_q = i_q - i_{q\_ref}$, $i_{d\_ref}$, $i_{q\_ref}$ are the reference values of the d- and q-axis components of the STATCOM output current; $k_{p1}$, $k_{p2}$, $k_{i1}$, $k_{i2}$ are the proportional and integral constants of the PI controller.

The dq axis transfer function block diagram of STATCOM under PI control can be obtained as shown in Figure 2:

![Figure 2. dq axis transfer function block diagram of STATCOM under PI control](image)

In order to improve the situation where the coefficient is difficult to set and the response speed is slow under PI control, non-linear control is used instead of PI control to process the error signal.

The dq axis transfer function block diagram of STATCOM under nonlinear control is shown in Figure 3:

![Figure 3. dq axis transfer function block diagram of STATCOM under nonlinear control](image)

Where: $i_a$, $i_b$, $i_c$ are instantaneous values of the three-phase current flowing into the STATCOM of the system.
After the error signals $\Delta i_d$ and $\Delta i_q$ are controlled by a non-linear method, the d and q-axis components of the STATCOM output voltage can be obtained through the calculation of equation (14).

The real-time measured STATCOM output reactive power $Q$ is processed to be different from the reference voltage $U_{ref}$ to obtain an error signal. Pass the error signal through the lead and lag link and the PI correction link, and finally obtain the trigger angle $\alpha$ in angle units $\alpha$. After the output signals $I_d$ and $I_q$ of STATCOM are subjected to non-linear control, the voltages $U_{iq}$ and $U_{id}$ output by STATCOM are obtained. The voltage $U_{aq}$, $U_{ad}$ of the access point can be obtained by connecting a transformer, three-phase synchronization signals $U_{sa}$, $U_{sb}$ and $U_{sc}$ can be obtained by dq / abc transformation, the phase angle of the synchronization signal can be obtained through the phase-locked loop, and finally the GTO trigger pulse is obtained according to the SPWM control principle, so as to control the voltage fluctuation and power angle deviation of the STATCOM balance system.

4. Digital simulation

4.1. Introduction to Simulation System

In this paper, PSCAD / EMTDC electromagnetic transient simulation software is used for verification. The effectiveness of the nonlinear method designed in this paper is illustrated by the effect of STATCOM in suppressing sub-synchronous oscillations, and compared with the PI control method, the advantages of the nonlinear method are highlighted. In the generator parameters and line model adopt the IEEE first standard sub-synchronous oscillation model, and STATCOM is installed on the generator outlet bus. Set the reference frequency to 60 Hz, the initial active power of the generator to 0.9 (pu), and the lagging power factor to 0.9. When the three-phase short-circuit fault at the generator outlet occurs at 1 s, the fault lasts 0.05s, and the simulation duration is 30s.

4.2. Analysis of simulation results

4.2.1. Relative to the mechanical position of the mass before and after STATCOM. In Figs. 4 and 5, delat_LPA and delta_LPB respectively indicate the mechanical positions of the masses of the low-pressure cylinder A and the low-pressure cylinder B relative to the generator.

Figure 4. Mechanical position of each mass relative to the generator before STATCOM

In Figs. 5 (a) and 5(c), the PI suffix represents PI control; in Figs. 5(b) and 5(d), the nonlinear suffix represents non-linear control.
4.2.2. Changes in angular velocity deviation before and after STATCOM. In Figures 6 and 7, $\Delta w$ represents the deviation between the angular speed of the generator and the rated speed.

**Figure 5.** Mechanical position of each mass relative to the generator after STATCOM

From Figure 4 to Figure 7, you can see:

1. **Before STATCOM:** After the three-phase short-circuit fault is removed, there is always a relative displacement between the masses of each shaft system, and the speed always fluctuates greatly. The sub-synchronous oscillation process fails to calm down, which will cause unstable system operation and even power generation. Serious consequences of damage to the main shaft of the unit.

2. **After inputting STATCOM:** After the three-phase short-circuit fault is removed, whether it is PI control or non-linear control, the relative displacement curve between the cylinders quickly converges to around 0, and the change in generator speed difference gradually decreases, so the sub-synchronous oscillation process was quelled and the system quickly stabilized. However, it can be clearly seen
from the curve that the curve convergence under the nonlinear control method is significantly faster than the PI control method, which is more beneficial to the stability of the system.

5. Conclusion
With the help of multi-input multi-output non-linear control strategy, a set of STATCOM control strategies superior to PI control is established. It has fast response ability of the non-linear control laws $u_1(t)$ and $u_2(t)$, and realizes the active control of the $dt$ component of the STATCOM compensation current, so as to compensate the reactive power faster, and finally subdue the sub-synchronous oscillation process. The simulation results show that the STATCOM control strategy designed by using the nonlinear control method has fast response speed and can effectively suppress sub-synchronous oscillation. The whole design process is simple and clear, and has certain application value.

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