Nonlinear Control of Static Synchronous Compensator (STATCOM) for Transmission System

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ABSTRACT

The Static Synchronous Compensator (STATCOM) is a shunt controller, which is a member of FACTS devices. In this paper, an effective and robust controller for STATCOM device on transmission lines, a Single Machine Infinite Bus (SMIB) system is modeled. A state space mathematical model is constructed which considers both electromechanical oscillations and reactive current of the STATCOM at the installation site. Based the obtained third-order model, state feedback linearization and linear quadratic regulation (LQR) approach are applied to obtain a nonlinear control law. The controllers are simulated and tested under different operating conditions comparing with the conventional PI controller.

KEYWORDS: FACTS; STATCOM; feedback linearization; nonlinear control; PI controller

I. INTRODUCTION

The power flows in some of the transmission lines are overloaded, which has as an overall situation requires the review of traditional transmission methods and practices, and the creation of new concepts, which would allow the use of existing generation and transmission lines up to their full capabilities without reduction in system stability and security. Series capacitor, shunt capacitor and phase shift are different approaches to increase the power system transmission lines load ability. They are very useful in a steady state operation of power systems but from a dynamical point of view, their time response is too slow to effectively damp transient oscillations.

As power system becomes more complex and more nonlinear loads are connected, the control of power system transient response is becoming a very critical issue. Therefore, it is necessary to study nonlinear control strategy to control the STATCOM dynamic characteristics and capabilities to improve transient stability [5].

Fig.1 A Typical STATCOM Connection to AC System
**MATHEMATICAL EQUATION**

A single machine infinite bus system (SMIB) is shown in Fig.2. The STATCOM is placed at the middle of the transmission line which is generally considered to be the ideal site.

![Diagram](image)

**Fig.2 A Single Machine Infinite Bus (SMIB) System with STATCOM**

The synchronous generator is represented by the classical second order model. The system dynamics is described by the following equations.

\[ \delta = \omega - \omega_0 \]  

(1)

\[ \dot{\omega} = \frac{\omega_0}{H} (P_m - P_e - \frac{D}{\omega_0} (\omega - \omega_0)) \]  

(2)

where \( P_e = \frac{E_q v_m}{X_1} \sin(\delta - \delta_m) \)  

(3)

The voltage magnitude and angle at bus m can be written as

\[ V_m = \left[ \frac{X_2 E_q \cos(\delta - \delta_m) + X_1 V_1 \cos \delta_m}{X_1 + X_2} \right] + \left[ \frac{X_1 X_2}{X_1 + X_2} I_q \right] \]  

(4)

\[ = V_{m0} + X_{eq} I_q \]  

(5)

\[ \delta_m = \tan^{-1} \left( \frac{X_2 E_q \sin \delta}{X_1 E_q \cos \delta + X_q V_1} \right) \]  

(6)

When the STATCOM is installed at the transmission line, the STATCOM reactive output current is given by the STATCOM control theory as

\[ I_q' = \frac{1}{T} (-I_q + Ku) \]  

(7)

The target of the nonlinear control strategy here is to keep the whole system stable by regulating the reactive power exchange between the STATCOM and ac system. For the system shown in Fig.2, the system stability can be evaluated by checking the absolute value of the relative angle of the generator within 180°. This relative angle is used as a stability index of the connected power systems. After a large disturbance, the smaller the relative angle is, the more stable the system shown in Fig.2, the system stability can be evaluated by regulating the reactive power exchange between the STATCOM and ac system. The nonlinear control design for the system using STATCOM is obtained as

\[ \dot{I}_q = \frac{1}{T} (-I_q + Ku) \]  

(11)

The output equation is

\[ y(t) = h(X(t)) = \delta \]  

(12)

The dynamic equation of a synchronous generator can be written in a state space as

\[ X(t) = f(X) + g(X)u \]  

(13)

\[ y(t) = h(X) \]  

(14)

where \( X = [\delta \ \omega \ I_q]^T \); \( u \) is the control variable of the STATCOM

\[ f(x) = \left[ \frac{\omega_0}{H} P_m - \frac{\omega_0}{H} C_1 (V_{m0} + X_{eq} I_q) - \frac{D}{H} (\omega - \omega_0) \right] \]  

\[ g(x) = \left[ 0 \ 0 \ \frac{K}{T} \right]^T \]  

(15)

(16)

\[ h(x) = \delta \]  

(17)

\[ C_1 = \frac{E_m}{X_1} \sin \left( \delta - \delta_m \right) \]  

(18)

**NONLINEAR CONTROL DESIGN OF THE STATCOM**

The development of the feedback linearization techniques provides a powerful tool for the design of controllers for nonlinear systems. The first step in the design procedure is the establishment of the linearization condition for the SMIB system. Hence the SMIB system has relative degree \( r=3 \), which is equal to the system order. A nonlinear system in \( X \) coordinate can be transferred into the following \( Z \) coordination

\[ z_1 = \delta \]  

(19)

\[ z_2 = \omega - \omega_0 = \Delta \omega \]  

(20)

\[ z_3 = \omega = \omega_0 - \frac{\omega_0}{H} C_1 (V_{m0} + X_{eq} I_q) - \frac{D}{H} \Delta \omega \]  

(21)

Then the nonlinear system can be transferred into a linear system of the form

\[ \dot{Z} = AZ + Bv \]  

(22)

\[ y = CZ \]  

(23)

where ‘\( v \)’ is the control input of the linear system and

\[ Z = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}, A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \]  

(24)

\[ C = [1 \ 0 \ 0], D = [0] \]  

(25)

The optimal control vector ‘\( v \)’ is

\[ v = -K^* Z = -k_1^* z_1 - k_2^* \Delta \omega - k_3^* \omega \]  

(26)

where \( k_1^* = 1.0, k_2^* = 7.6, k_3^* = 3.9 \)

The nonlinear control design for the system using STATCOM is obtained as
\[ u = \frac{\alpha(x)}{\beta(x)} + \frac{1}{\beta(x)}v \]  
(28)

\[ \alpha(x) = \frac{\tan \theta}{V} C_1 X_{eq} I_q \]  
(29)

\[ \beta(x) = -\frac{K_0}{V} C_1 X_{eq} \]  
(30)

\[ u = \frac{H}{K C_1 X_{eq} \omega_o} (k_1 \delta + k_2 \Delta \omega + k_3 \omega) + \frac{1}{K} I_q \]  
(31)

**PI CONTROL SCHEME OF STATCOM**

The effectiveness of the proposed nonlinear controller in damping power system oscillations is evaluated through a comparison with a conventional PI controller shown in Fig.3. The gains of controller were selected based on a pole placement technique.

The method produces an optimum control function for linear system designed for a specific operating point. The transfer function of PI controller is given as

\[ G_{PID}(s) = K_P + \frac{K_I}{s} \]  
(32)

The controller transfer function can be written as

\[ G_c(s) = \frac{T_{w} s + K_P}{s + T_{w} K_I} \]  
(33)

Here, \( K_P \) and \( K_I \) are the gains in proportional and integral loops, \( T_w \) is the washout time constant.

**SIMULATION RESULTS**

The performance of the STATCOM for the stabilization of synchronous generator is evaluated by computer simulation studies. The STATCOM is installed at the middle of the transmission line. The time constant of the STATCOM reactive output current is set to 0.01 sec. The transient performances of the rotor angle are shown in Fig.4 when the generator is loaded at power 0.8 p.u. Fig.5 shows the transient response of the mid-bus voltage. It can be seen that from the simulation results, the nonlinear control is superior over the conventional PI control not only in suppressing the STATCOM bus voltage fluctuation, but also in restraining the power oscillation.

The transient performances of the rotor angle are shown in Fig.6 when the generator is loaded at power 1.0 p.u. Fig.7 shows the transient response of the mid-bus voltage. When the generator load was increased (P=1.0 p.u), STATCOM with conventional PI control are more unstable, but the STATCOM using nonlinear control is effectively damps the system oscillation and completely stable at 7 second. This proved that nonlinear control technology provides new promising way to further improve the operation security and dynamic performance of the system.
CONCLUSION

The control strategy of a STATCOM in a single machine infinite bus system was derived to improve system stability and damping power system oscillation. The control of the STATCOM is selected based on the linearized mathematical model of the system by applying nonlinear control. The effectiveness of the proposed control strategy in improving the power system dynamic stability has been verified through nonlinear time-domain simulations under different load conditions. This control approach for STATCOM shows better performance compare with the conventional PI controller.

REFERENCES


