STATCOM Control for Power System Voltage Control Applications

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***Abstract*—A Static Compensator (StatCom) is a device that can provide reactive support to a bus. It consists of voltage sourced converters connected to an energy storage device on one side and to the power system on the other. In this paper, the conventional method of PI control is compared and contrasted with various feedback control strategies. A linear optimal control based on LQR control is shown to be superior in terms of response profile and control effort required. These methodologies are applied to an example power system.**

***Index Terms*—Controller design, StatCom, voltage regulation.**

I. INTRODUCTION

THE USE OF FACTS (flexible AC transmission system) devices in a power system can potentially overcome limitations of the present mechanically controlled transmission systems. By facilitating bulk power transfers, these interconnected networks help minimize the need to enlarge power plants and enable neighboring utilities and regions to exchange power. The stature of FACTS devices within the bulk power system will continually increase as the industry moves toward a more competitive posture in which power is bought and sold as a commodity. As power wheeling becomes increasingly prevalent, power electronic devices will be utilized more frequently to insure system reliability and stability and to increase maximum power transmission along various transmission corridors.

The static synchronous compensator, or StatCom, is a shunt connected FACTS device. It generates a balanced set of three-phase sinusoidal voltages at the fundamental frequency, with rapidly controllable amplitude and phase angle. This type of controller can be implemented using various topologies. However, the voltage-sourced inverter, using GTO thyristors in appropriate multi-phase circuit configurations, is presently considered the most practical for high power utility applications [1]–[3]. A typical application of this type of controller is voltage support.

Fig. 1 shows the StatCom connection to a utility bus. The GTO inverter shown in the figure consists of several six step voltage sourced inverters. These inverters are connected by means of a multi-winding transformer to a bus. The use of several inverters reduces the harmonic distortion of the output voltage. The inverters are connected to a capacitor which carries the DC voltage.

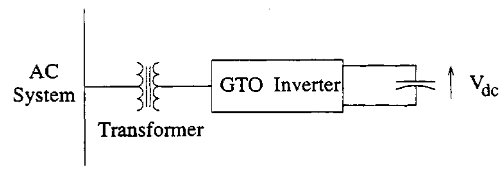

Fig. 1. Connection of a StatCom to a bus.

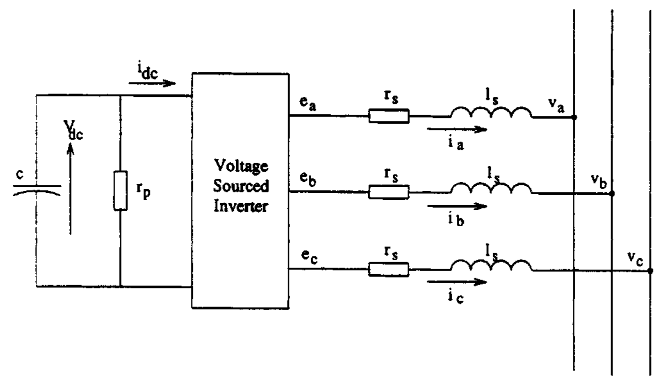

Fig. 2. Equivalent circuit of StatCom.

In practice, conventional proportional-integral (PI) control is typically used to achieve automatic voltage regulation. The standard response time is typically chosen to be on the order of a hundred microseconds (~ 0.1 s) [2]. In this paper, several state feedback control methods are developed and shown to have superior performance to the PI controller in terms of response dynamics and control effort required.

II. MODELING OF THE STATCOM

The equivalent circuit of the StatCom is shown in Fig. 2. In this circuit, the resistance r_s in series with the inverter represents the sum of the transformer winding resistance losses and the inverter conduction losses. The inductance l_s represents the leakage inductance of the transformer. The resistance r_p in shunt with the capacitor c represents the sum of the switching losses of the inverter and the power loss in the capacitor. The inverter block represents a lossless transformer. The voltages e_a, e_b and e_c are the inverter AC side phase voltages suitably stepped up. The loop equations for the circuit may be written in vector form as [4]:

$$\frac{d}{dt} i_{abc} = -\frac{r_s}{l_s} i_{abc} + \frac{1}{l_s} (e_{abc} - v_{abc}) \tag{1}$$

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The a phase bus voltage is given by

$$v_a = \sqrt{2}\, V_s \cos(\omega_s t + \theta_s) \tag{2}$$

where V_s is the rms value of the phase voltage at the bus and θ_s is the phase angle.

The output of the StatCom (neglecting harmonics) may be expressed as

$$e_a = kV_{\mathrm{dc}} \cos(\omega_s t + \alpha) \tag{3}$$

where

V_{dc} is the DC-side voltage,
α is the phase angle of the voltage and
k is a factor that relates the DC voltage to the peak voltage on the AC side.

Transforming the system to a synchronous reference frame and scaling the equations (where the primed quantities indicate per unit) results in the following model:

$$\frac{d}{dt}\begin{bmatrix} i'_d \\ i'_q \\ V'_{\mathrm{dc}} \end{bmatrix} = A_s \begin{bmatrix} i'_d \\ i'_q \\ V'_{\mathrm{dc}} \end{bmatrix} - \frac{\omega_s}{L'_s}\begin{bmatrix} V_s \cos\theta_s \\ V_s \sin\theta_s \\ 0 \end{bmatrix} \tag{4}$$

where

$$A_s = \begin{bmatrix} \dfrac{-R'_s\omega_s}{L'_s} & \omega_s & \dfrac{\omega_s k}{L'_s}\cos(\alpha+\theta) \\ -\omega_s & \dfrac{-R'_s\omega_s}{L'_s} & \dfrac{\omega_s k}{L'_s}\sin(\alpha+\theta) \\ M_k\cos(\alpha+\theta) & M_k\sin(\alpha+\theta) & \dfrac{-C'\omega_s}{R'_p} \end{bmatrix} \tag{5}$$

and

$$M_k = -\tfrac{3}{2} k\omega_s C' \tag{6}$$

Note that although (4) appears to be linear, it is actually nonlinear. The nonlinearity of the StatCom is manifested by the inclusion of the state equation for the control angle α. Changes in the control angle α will results in nonlinear responses in the StatCom states i_d, i_q and V_{dc}.

The injected active and reactive power at the StatCom bus are given by

$$P = V_s(\cos\theta_s i_d + \sin\theta_s i_q) \tag{7}$$

$$Q = V_s(\sin\theta_s i_d - \cos\theta_s i_q) \tag{8}$$

The characteristic equation of the linearized system of (4) is given by

$$\begin{aligned} s^3 &+ s^2\left\{\frac{2R'_s\omega_s}{L'_s} + \frac{\omega_s C'}{R'_p}\right\} \\ &+ s\left\{\frac{R'_s\omega_s}{L'_s}\left(\frac{R'_s\omega_s}{L'_s} + \frac{2\omega_s C'}{R'_p}\right) + \omega_s^2 + \frac{3}{2}\frac{k^2\omega_s^2 C'}{L'_s}\right\} \\ &+ \left\{\frac{\omega_s^3 C'}{R'_p}\left(1 + \frac{R_s'^2}{L_s'^2}\right) + \frac{3}{2}\frac{k^2\omega_s^3 C' R'_s}{L_s'^2}\right\} = 0 \end{aligned} \tag{9}$$

Note that (9) indicates that the eigenvalues [roots of (9)] are independent of the control angle, α. This means that the stability of the StatCom itself is independent of the control strategy applied.

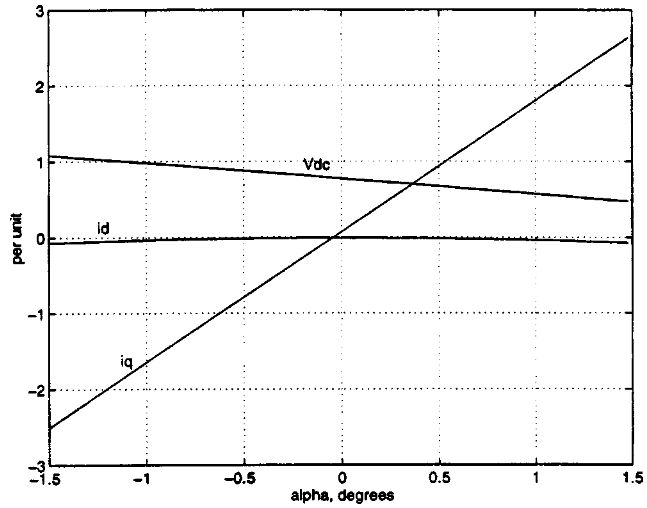

Fig. 3. Steady-state operating points.

The StatCom parameters (in pu) used in the following discussions are given in [4] and are repeated here:

$$\begin{aligned} L'_s &= 0.15, & C' &= 0.88, & k &= 4/\pi \\ R'_s &= 0.01, & R'_p &= 100/k, & \omega_b &= 377.0 \end{aligned}$$

These StatCom parameters yield the following eigenvalues of the linearized system:

$$s = -23.8, \qquad -15.4 \pm j1473.0$$

Note that these eigenvalues indicate that the StatCom is a highly damped and stable system at this operating point. The set of complex eigenvalues indicate the existance of a high frequency oscillation in the dynamic response of the StatCom.

A plot of the steady-state operating condition of the StatCom as a function of the control angle α using the parameters given previously is shown in Fig. 3. Note that although this is a plot of the nonlinear state relationships, the current component i'_q varies almost linearly with α. Since the reactive power supplied by the StatCom depends almost solely on i'_q (i'_d simply supplies the active power losses), the reactive power supplied by the StatCom also varies nearly linearly with α. This leads to the voltage at the StatCom bus being nearly linearly dependent on the control angle α as well. Thus, linear methods of control will yield satisfactory results for a wide range of disturbances, even though the StatCom and power system are inherently nonlinear.

The nonlinear power system may be modeled as:

$$\dot{x} = f(x, z) \tag{10}$$

$$\dot{y} = g(y, z) \tag{11}$$

$$0 = h(x, y, z) \tag{12}$$

where x represents the generator states of the system (such as generator rotor angle and speed, dq axis voltages, excitation system states, etc.) and (10) represents the n sets of dynamic models corresponding to the generators. The states y represent the StatCom states and (11) represents the StatCom dynamic model given in (4). The states z represent the bus voltage mag-