Design of a STATCOM Controller Using Pole-Assignment Technique

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Abstract

A Static synchronous compensator(STATCOM) is one of the new generation flexible AC transmission system (FACTS) devices with a promising feature of applications in power system. STATCOMs are used to stabilize the system by exchanging reactive power with the power system. In this article, dynamic behavior of a single machine infinite bus power system with STATCOM has been investigated. A 5^{th} order dynamic model has been used for damping control study. The effect of PID controller in damping enhancement has been investigated. A pole-placement method has been employed to find the gain settings of the controller. The designed controller has been tested for a number of disturbance conditions including symmetrical three phase fault and variation of the operating conditions. It was observed that the designed PID controller can provide damping to the system. The gain settings, however, have to be tuned for different operating conditions.

Keywords: Power System, FACTS, STATCOM, Damping control, Pole-placement, Eigen value search, PID controller

1. Introduction

Reactive power compensation is known to increase the power transmission in AC lines. Fixed or mechanically switched capacitors and reactors have long been employed to increase the steady-state power transmission by controlling the voltage profile along the lines [1].

Controllable synchronous voltage sources known as static compensators, are a recent introduction in power system for dynamic compensation and for real time control of power flow.The static compensator (STATCOM) provides shunt compensation in a way similar to the static var compensators (SVC), but utilize a voltage source converter rather than shunt capacitors and reactors [2]. STATCOM is an active device, which can control voltage magnitude and phase in a very short time and therefore has the ability to improve the system damping as well as voltage profiles of the system. It has been reported that STATCOM can offer a number of performance advantages for reactive power control applications over the conventional SVC because of its greater reactive current output at depressed voltage, faster response, better control stability, lower harmonics and smaller size, etc. [3]

Two basic controls are implemented in a STATCOM [3, 4]. The first is the AC voltage regulation of the power system, which is realized by controlling the reactive power interchange between the STATCOM and the power system. The other is the control of the DC voltage across the capacitor through which the active power injection from the STATCOM to the power system is controlled [3, 5]. The effect of stabilizing controls on STATCOM controllers have been investigated in several recent papers [3, 4, 5, 6].

In this article, a single machine infinite-bus system with a long transmission network with STATCOM installed at its mid point has been studied. The effectiveness of implementing PID control in the AC voltage magnitude control loop was investigated. The gain setting of the PID controller were obtained by using the pole assignment method [7]. The effectiveness of the controller is tested by simulating the power system installed with STATCOM for a number of disturbance conditions. The simulation results indicates that the PID controller has an impact on damping enhancement of the system.

2. Power System Model

A single machine infinite bus system with STATCOM installed at the mid point of the transmission line is shown in Fig.1. The system consists of a step down transformer (SDT) with a leakage reactance X_{SDT}, a three phase GTO-based voltage sources converter (VSC) and a DC-capacitor. The STATCOM is modeled as a voltage sourced converter behind a step down transformer. The VSC generates a controllable AC-voltage source $v_o(t) = V_o sin(\omega t - \psi)$ behind the leakage reactance. The voltage difference between the STATCOM-bus AC voltage V_L and V_o produces active and reactive power exchange between the STATCOM and the power system, which can be controlled by adjusting the magnitude V_o and the phase ψ.

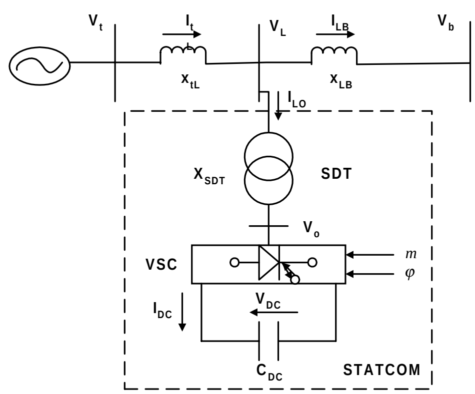

Figure 1: STATCOM installed in a single machine infinite bus power system.

The voltage current relationship in the STATCOM are expressed as [4],

$$\begin{aligned}
\bar{I}_{Lo} &= \bar{I}_{Lod} + j\bar{I}_{Loq} \\
V_o &= eV_{DC}(\cos\psi + j\sin\psi) = eV_{DC}\angle\psi \\
\frac{dV_{DC}}{dt} &= \frac{I_{DC}}{C_{DC}} = \frac{e}{C_{DC}}(I_{Lod}\cos\psi + I_{Loq}\sin\psi)
\end{aligned} \tag{1}$$

where, for the PWM inverter,

$$\begin{aligned}
e &= mk; \\
k &= \frac{\text{AC Voltage}}{\text{DC Voltage}}; \\
m &= \text{modulation ratio defined by PWM}; \\
\psi &= \text{phase angle, defined by PWM}
\end{aligned}$$

From (1), it can be seen that the magnitude of the STATCOM voltage V_{DC} depends on e, which is a measure of the magnitude of the STATCOM voltage.

The nonlinear model of the power system of Fig. 1 is given as:

$$\begin{aligned}
\dot{\delta} &= \omega_b\omega \\
\dot{\omega} &= \frac{1}{M}[P_m - P_e - D\omega] \\
\dot{eq}' &= \frac{1}{T_{do'}}[E_{fd} - eq' - (x_d - x_d')I_{tLd}] \\
\dot{E}_{fd} &= -\frac{1}{T_A}(E_{fd} - E_{fdo}) + \frac{K_A}{T_A}(V_{to} - V_t) \\
\dot{V}_{dc} &= \frac{e}{C_{DC}}[I_{lod}\cos\psi + I_{loq}\sin\psi]
\end{aligned} \tag{2}$$

By linearizing equations for I_{tld} , I_{tlq} I_{tlod} , I_{loq} and then substituting in (2), the linearized system equation can be written as

$$\begin{aligned}
\Delta\dot{\delta} &= \omega_b\Delta\omega \\
\Delta\dot{\omega} &= \frac{(-\Delta P_e - D\Delta\omega)}{M} \\
\Delta\dot{eq}' &= \frac{(-\Delta eq + D\Delta E_{fd})}{T_{do}'} \\
\Delta\dot{E}_{fd} &= -\frac{1}{T_A}(\Delta E_{fd} - K_A\Delta V_t)
\end{aligned} \tag{3}$$

$$\begin{aligned}
\Delta\dot{V}_{DC} &= \frac{1}{C_{DC}}[(I_{lod_0}cos\psi_0 + I_{loq_0})\Delta e + e_0(-I_{lod_0}sin\psi_0 \\
&\quad + I_{loq_0}cos\psi_0)\Delta\psi + \\
&\quad e_0(cos\psi_0\Delta I_{lod} + sin\psi_0\Delta I_{lod})]
\end{aligned} \tag{4}$$

where,

$$\begin{aligned}
\Delta P_e &= K_1\Delta\delta + K_1\Delta eq' + K_{pDC}\Delta V_{DC} + K_{pc}\Delta e \\
&\quad + K_{p\psi}\Delta\psi
\end{aligned} \tag{5}$$

$$\begin{aligned}
\Delta eq &= K_4\Delta\delta + K_3\Delta eq' + K_{qDC}\Delta V_{DC} + K_{qc}\Delta e \\
&\quad + K_{q\psi}\Delta\psi
\end{aligned} \tag{6}$$

$$\begin{aligned}
\Delta V_t &= K_5\Delta\delta + K_6\Delta eq' + K_{vDC}\Delta V_{DC} + K_{vc}\Delta e \\
&\quad + K_{v\psi}\Delta\psi
\end{aligned} \tag{7}$$

the linearized system equations can be expressed as

$$\dot{x} = Ax + Bu \tag{8}$$

where x is the vector of the states $[\Delta\delta\ \ \Delta\omega\ \ \Delta eq'\ \ \Delta E_{fd}\ \ \Delta V_{DC}]$ and the control vector u comprises of $[\Delta e\ \ \Delta\psi]'$. Fig. 2 shows the block diagram for the system.

3. PID Controller Design by Pole-Assignment method

It has been reported in the literature that control in the phase angle control loop alone is not effective in providing damping to the system [4]; hence

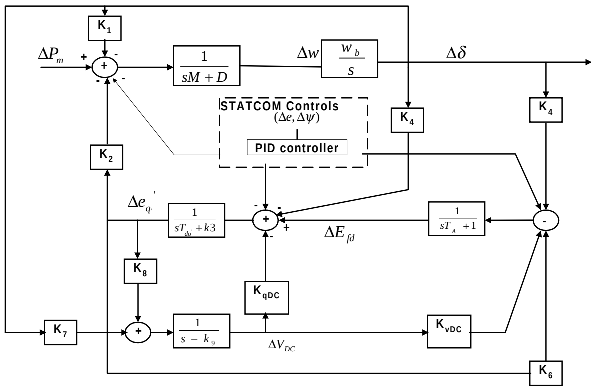

Figure 2: Block diagram of the linearized system installed with STATCOM.

it is not considered in this article. A controller in the voltage magnitude loop has been designed. Fig. 3 shows the block diagram of a PID controller in the magnitude control circuit. K_p, K_I and K_d are the gains of the PID controller and T_w is the washout time constant. In the design of a fixed parameter PID controller, the gain settings can be computed by assigning the eigen values at pre-specified locations. This is usually referred to as the pole-assignment method. The approach begins with linearizing the nonlinear model around a nominal operating point to obtain the desired linear model which is described by the input-output equations

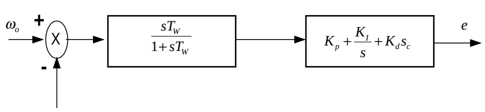

Figure 3: The Magnitude control block diagram.

$$\dot{x} = Ax + Bu \tag{9}$$

$$y = Cx + Du \tag{10}$$

where x, y and u are states vector variables, output signal and control signal respectively. Taking the Laplace transform and substituting the output equations into the state equation gives

$$X(s) = (sI - A)^{-1}BU(s) \tag{11}$$

If the system output Y is fed to the input of the PID controller having a transfer function $H(s)$, we can write the control signal as

$$U(s) = H(s)Y(s)$$

where,

$$H(s) = \frac{sT_w}{1 + sT_w}(K_p + \frac{K_I}{s} + K_d s) \tag{12}$$

Substituting (12) into (11) , we get

$$X(s) = (sI - A)^{-1}BH(s)CX(s) \tag{13}$$

or

$$[1 - (sI - A)^{-1}BH(s)C]X(s)] = 0 \tag{14}$$

If λ is the assigned eigen value of the closed-loop system equipped with the PID STATCOM controller, then

$$det[1 - (\lambda I - A)^{-1}BH(\lambda)C] = 0 \tag{15}$$

Using the identity of determinants [8]

$$det[1 - D.B] = det[1 - B.D] \tag{16}$$

Eq. (15) can be written as

$$1 - C(\lambda I - A)^{-1}BH(\lambda) = 0 \tag{17}$$

or

$$H(\lambda) = \frac{1}{1 - C(\lambda I - A)^{-1}B} \tag{18}$$

$$\frac{\lambda T_w}{1 + \lambda T_w}K_p + \frac{T_w}{1 + T_w}K_I + \frac{\lambda^2 T_w}{1 + \lambda^2 T_w}K_d = \frac{1}{1 - C(\lambda I - A)^{-1}B} \tag{19}$$

Selecting the dominant eigen values at a desired location $\lambda = \sigma + j\omega_d$, and separating the real and imaginary parts of (19) results in two equations in terms of 3 gain parameters. A third equation is obtained by pre-specifying another real pole.

4. Simulation Results

The power system with the STATCOM controller has been simulated to deliver a nominal power output of 0.9 at unity power factor load. Under normal operating conditions, the eigen values of the open loop system are -99.1923, $-0.3274 \pm j4.624$, -0.05278 and -1.0901. It is observed that the damping for the electromechhanical mode (characterized by the pair of eigen values of $-0.3274 \pm j4.624$) is not satisfactory. These should be shifted leftwords to more desirable locations. For eigenvalues $-3 \pm j10$ and -1.091 (18) yields the following gain parameters.

$$
\begin{aligned}
K_p &= 5.4928 \\
K_I &= 2.18409 \\
K_d &= 3.2166
\end{aligned} \tag{20}
$$

To demonstrate the effectiveness of the PID controller in providing damping, the system has been simulated over a wide range of disturbance conditions including input torque variations, operating condition variations and three phase fault at the infinite bus. Non linear system model has been considered and simulation has been done by using SIMULINK software.

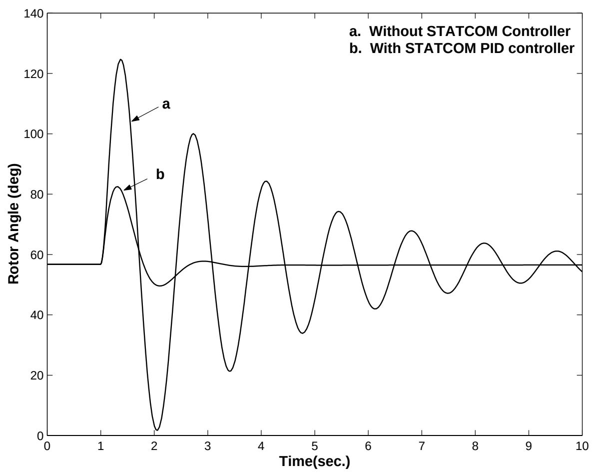

Figure 4: Rotor Angle variation for a 100 % input torque pulse with (a)no stabilizing control (b)PID control

Fig. 4 - 5 shows respectively the variation of rotor angle and the STATCOM bus voltage for a disturbance of 100% mechanical torque for 0.05 sec. The response without controller was found to be completely oscillatory shown by curve a, while curve b shows the response with PID controller. Fig. 5 shows that the mid-bus voltage experiences a sudden peak with the application of the PID control.

The gain coefficient K_p, K_i and K_d depends on the system operating condition. For example, for generator power output of 1.0 pu at 0.8 leading power factor, the coefficients are

$$
\begin{aligned}
K_p &= 7.74 \\
K_I &= 4.495 \\
K_d &= 2.81
\end{aligned} \tag{21}
$$

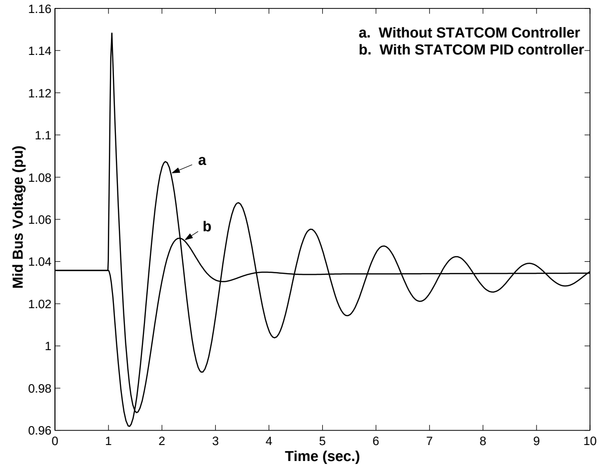

Figure 5: Mid-bus voltage variations corresponding to Fig. 4

The transient rotor angle variation for a 100 % torque pulse is shown in Fig. 6 for the two gain settings (20) and (21). These are shown by curves a and b respectively. This is one of the apparent difficulties of the pole-placement technique that the gains have to be retuned for various loading conditions.

The controller was then tested for a three phase fault for 0.1 sec at infinite bus of the power system. The pre-fault loading is 0.9 pu. and parameters values (20) were used for the PID control. Fig. 7 shows the angular speed variation of the generator. The uncontrolled response, shown by curve a , is oscillatory. The PID controller provides good damping to the system as shown by curve b.

5. Conclusion

A pole-placement technique has been used to design PID controller for the magnitude control loop of the STATCOM located at the mid-point of a SMIB power system. The effectiveness of the controller for damping enhancement has been tested for different disturbance conditions including three phase fault. The designed controller has been found to be very effective in providing damping to the system. The gain settings however need to be tuned for different operating conditions.

References

[1] Laszlo Gyugi. Dynamic compensation of AC transimssion line by solid state synchronous voltage

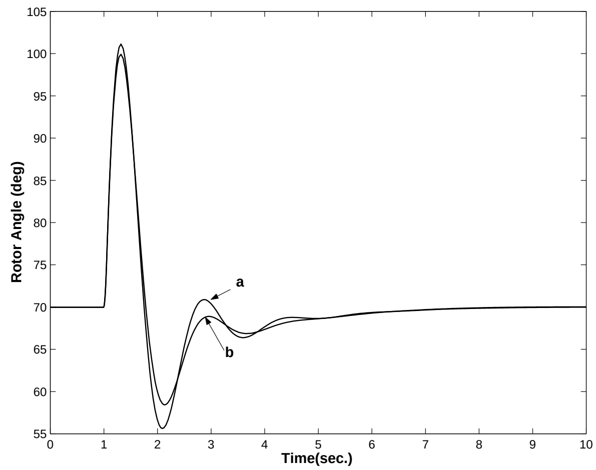

Figure 6: Rotor Angle variation for a 100 % torque pulse with , (a) PID gain calculated at 0.9 pu loading (b) PID gain calculated at 1 pu loading

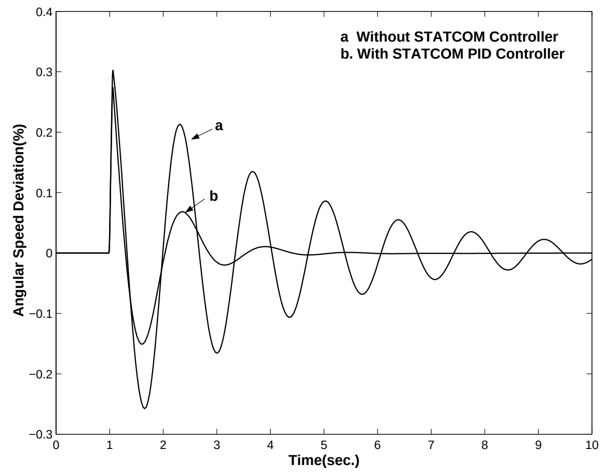

Figure 7: Angular speed variations for three phase fault at infinite bus with ,(a)no control (b) PID control

sources. *IEEE transaction on power delivery.*, vol. 9 No.2 :904–911, April 1994.

[2] J. Machowski. *Power System Dynamics and Stability.* Johan Wiley and Sons,1997.

[3] C. Li, Q. Jiang and F. Li. Design of Rule Based Controller for STATCOM. *Proc. of 24th Annual Conf. of IEEE Ind. Electronicns Society, IECon '98.*, 467–472, 1998.

[4] H. F. Wang. Phillip-Heffron Model of Power System Installed with STATCOM and Applications. *IEE Proc. Gen. Trans. and Ditr.*, vol 146, No. 5 : 521-527

[5] H. F. Wang and F. Li. Design of STATCOM Multivariable Sampled Regulator. *Int. Conf. on Electic Utility Deregulation and Power Tech. 2000, City University of Londonoc.*, April 2000.

[6] K. R. Padiyar and A. M. Kulkarni. Analysis design of voltage control of Static Condenser. *IEEE Conf. On power electronics, derives energy system for industrial growth.*, vol. 1, :393-398 April 1996.

[7] Yuan-Yih Hsu and Chao-Rong Chen. Tuning of power system stabilizers using an artificial neural network. *IEEE Tranactions on Energy Conversion.*, vol. 6 No.4, :612-619 December 1991.

[8] T. Kailath *Linea Systems.* Englewood Cliffs, NJ: Prentice Hall, , 1980 page 651.

[9] A. H. M. A Rahim, S. A. Al-Baiyat and F.M Kandlawala. A Robust STATCOM Controller for Power System Dynamic Performance Enhancement. *2001 IEEE Power Engineering Society Summer Meeting Vancouver Canada.*, July 2001.

Appendix

System Paramters (in p.u. except indicated)
$H = 3s.$, $T_{do}^{'} = 6.3$, $x_d = 1.0$,$x_d' = 0.3$, $x_q = 0.6$. $D = 4.0$, $x_{TL} = 0.3$, $x_{LB} = 0.3$, $x_{SDT} = 0.15$, $K_A = 10.0$,$T_A = 0.01s.$, $T_C = 0.05s.$, $C_{DC} = 1.0$, $c_o = 0.25$, $\psi_o = 46.52°$, $T_w = 1sec.$

Nominal Plant Operating condition :
$P_{eo} = 0.9$, $V_{to} = 1.0$, p.f. $= 1.0$