An LQR/Pole Placement Controller Design for STATCOM

Amin Valipour Arkhloo
Address:first floor-Apt6-morvarid alley-sadaf-ponakebakhtari Avenue-shharke gharb-tehran
E-mail:amincpe@yahoo.com

Abstract:*The static synchronous compensator (STATCOM)is gaining extensive popularity in power system applications. In general, power factor and stability of the utility system can be improved by STATCOM. Specifically, STATCOM can stabilize a given node voltage and compensate for the power factors of the equipment serviced by that node. So STATCOM is a multiple input, multiple output nonlinear system. In this paper, we want to design a controller for STATCOM by using LQR and pole assignment methods. Simulation results show that the proposed STATCOM controller can effectively increase transient stability of the power system even in the presence of a large operation point.*

Keywords: STATCOM, LQR, pole assignment, controller

1 Introduction

Reactive power compensation is an important problem. In the past before using STATCOM, reactive power compensators were based on power electronic devices, such as Thyristors. These devices improved the dynamics and precision but the transient response was slow. With the developments in power electronics a new kind of compensators were introduced. This compensator is called the Static Synchronous Compensator (STATCOM). STATCOM is able to improve both the transient and steady state responses of the system under consideration. Therefore, STATCOM is very effective in power systems. Moreover, much research confirms several advantages of STATCOM[1]-[3]. These advantages include:

- Decrease in size, weight and cost.
- Equality of lagging and leading output.
- Precise and continuous reactive power control system with fast response.
- Possible active harmonic filter capability.

Much work about STATCOM's steady state performance control has been done, which is based on diagram analysis and control approaches, usually a proportional integrated controller (PI controller), is convenient in the traditional power systems analysis method and it is not necessary to build a special mathematical model for controller design. In the PI method controller , the system response is slow due to the calculation of active and reactive power, which needs several periods(T) of the power system ,and seems ineffective when the variations of the power system is fast and the design of the PI controller takes place in frequency domain[7]. As power system becomes more complex and more nonlinear loads are connected, the control of power system's transient response becomes very hard, therefore (PI) method is not suitable and is necessary to introduce a dynamics model for STATCOM and design a controller that has taken the dynamic model into account. The calculation of active and reactive power based on frequency domain is not necessary for controlling STATCOM's dynamic performance. In fact, the instantaneous values of power system parameters are used in STATCOM dynamic control, which means the response of STATCOM can be within one power system period. In this paper, we want to design a controller for STATCOM by using the LQR method and pole assignment, in order to find which method is suitable for STATCOM. Most of our work in this paper tries to decouple the states.

2 Circuit model

Figure 1 is the circuit diagram of a typical STATCOM:

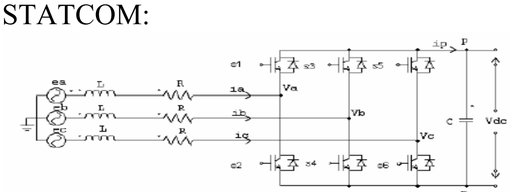

Figure1: Equivalent circuit of STATCOM

Based on the equivalent circuit of STATCOM shown in figure1 we can achieve an equation state space for STATCOM as below:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega & -\frac{D_d}{3L} \\ -\omega & -\frac{R}{L} & -\frac{D_q}{3L} \\ \frac{3}{2C}D_d & \frac{3}{2C}D_q & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{3L} \\ 0 \\ 0 \end{bmatrix} V_m \qquad (1)$$

From the model we can see that the states of the STATCOM dynamics loop are i_d, i_q, V_{dc} . V_m can be a system constant parameter. The control variables are D_d and D_q .Note that this is a nonlinear system. In the model, we selected the circuit parameters for the circuit shown in (1), and circuit parameters are selected as below:

$$R = 0.02\Omega; L = 2.8e-03H; C = 0.1F; V_m = 5882V; \omega = 377(\frac{rad}{s})$$

Desired steady states:

$$V_{dc} = 10000\,V$$
$$i_d = 0A$$
$$i_q = 178\,A$$
$$D_d = 0$$
$$D_q = 0.6445$$

The problem is how we can deal with the nonlinear characteristics in the controlled STATCOM. There are different methods, which can be used to control a nonlinear system. Since we know the operating points of the STATCOM we can use the linearization method to cope with this nonlinear problem. Matrixes linearized around the operating points of x^0 and u^0 , are shown below:

$$\dot{x} = Ax + Bu$$
$$y = cx \qquad (2)$$

$$A = \left.\frac{\partial f}{\partial x}\right|_{(x^0,u^0)} \qquad (3)$$

$$B = \left.\frac{\partial f}{\partial u}\right|_{(x^0,u^0)} \qquad (4)$$

With operating points as below:

$$x^0 = \begin{bmatrix} i_{d_0} \\ i_{q_0} \\ V_{dc_0} \end{bmatrix}, u^0 = \begin{bmatrix} D_{d_0} \\ D_{q_0} \end{bmatrix} \qquad (5)$$

Here we compute the matrixes Jacobian as below:

$$A = \left.\frac{\partial f}{\partial x}\right|_{(x^0,u^0)} = \begin{bmatrix} \frac{-R}{L} & \omega & \frac{-D_{d_0}}{3L} \\ -\omega & \frac{-R}{L} & \frac{-D_{q_0}}{3L} \\ \frac{3D_{d_0}}{2C} & \frac{3D_{q_0}}{2C} & 0 \end{bmatrix} \qquad (6)$$

$$B = \left.\frac{\partial f}{\partial u}\right|_{(x^0,u^0)} = \begin{bmatrix} \frac{-V_{dc_0}}{3L} & 0 \\ 0 & \frac{-V_{dc_0}}{3L} \\ \frac{3i_{d_0}}{2C} & \frac{3i_{q_0}}{2C} \end{bmatrix} \qquad (7)$$

Equations state space that we want to control are as below:

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{V}_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & \omega & \frac{-D_{d_0}}{3L} \\ -\omega & \frac{-R}{L} & \frac{-D_{q_0}}{3L} \\ \frac{3D_{d_0}}{2C} & \frac{3D_{q_0}}{2C} & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} + \begin{bmatrix} \frac{-V_{dc_0}}{3L} & 0 \\ 0 & \frac{-V_{dc_0}}{3L} \\ \frac{3i_{d_0}}{2C} & \frac{3i_{q_0}}{2C} \end{bmatrix} u \qquad (8)$$

$$Y = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} \qquad (9)$$

Operating points for STATCOM are:

$$V_{dc} = 10000\ V; i_d = 0; i_q = 178\ A;$$
$$D_{d_0} = 0; D_{q_0} = 0.6445;$$

Thus we get

$$A = \begin{bmatrix} -7.1429 & 377.0000 & 0 \\ -377.0000 & -7.1429 & 9.6675 \\ 0 & 9.6675 & 0 \end{bmatrix}$$

$$B = 1.0e+006 \times \begin{bmatrix} -1.1905 & 0 \\ 0 & -1.1905 \\ 0 & 0.0027 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

All of variables can be measured from the power system, which means the system is observable.However we only have two independent control inputs and three system states. We need to see if the system is controllable. The controllability matrix is defined as below:

$$C_O = \begin{bmatrix} B & AB & A^2 B \end{bmatrix}$$

Thus controllability matrix C_0 is

$$C_O = 1.0e+010 \times \begin{bmatrix} 9.9252 & 0.0001 & 0 \\ 0.0001 & 9.9165 & -0.0424 \\ 0 & -0.0424 & 1.0420 \end{bmatrix}$$

$$\det(C_O) = 1.0254+032$$

The open loop linearized system's eigenvalues are:

$$\Lambda = \begin{bmatrix} -7.12 + 3.7798\,i \\ -7.12 - 3.7798\,i \\ -0.04 \end{bmatrix} \times 1.0e-02$$

Since all the eigenvalues of the system are on the left hand of the plane, the system is stable. In the open loop system response shown in figure 2 there are large oscillations in i_d and i_q during 0.0-0.6sec and V_{dc} is not constant.

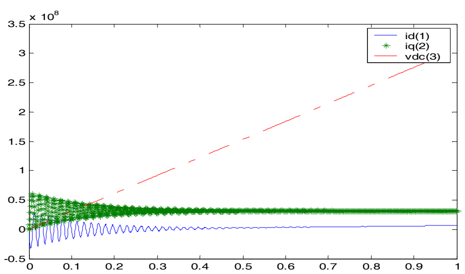

Figure 2:open loop response

Since the STATCOM is used for instantaneous reactive power compensation for power systems, the i_q 's transient response should be within one period of power system[4].The frequency of the power system is 60 Hz, which means that one period is about 0.017sec.Thus the i_q transient response time should be less than 0.017sec.In this time the voltage of the capacitor V_{dc} should be kept constant[3].The control effort of D_d and D_q should be within [-1,+1],see[5].

When we look at the open loop system response figure2, we can see several dynamic characteristics need to be improved:

1) The eigen values of i_q and i_d are poorly damped.
2) The settling times of i_d and i_q are larger than the time requied.
3) The overshoot of i_d and i_q is large.
4) The voltage of the capacitor V_{dc} doesn't remain around a steady constant value 10000v.

There are two main design methods. Pole assignment design and LQR design. we will discuss these two methods used in STATCOM controller design.

3 pole assignment controller design

In this method, closed loop pole selection is an important part of the design which should be correct and provide the desired steady state, and so the control effort should be within acceptable range.

3.1 control algorithm

For a given system as below:

$$\dot{x} = Ax + Bu \tag{10}$$

$$Y = Cx \tag{11}$$

If we set the controller as

$$u(t) = -kx(t) \tag{12}$$

Then the closed loop state equation can be obtained as:

$$\dot{x} = [A - Bk]x(t) \tag{13}$$

The closed loop eigenvalues and eigenvectors are related by the equation:

$$[A - Bk]V_i = \lambda_i V_i \tag{14}$$

This equation can be put in the form

$$\begin{bmatrix} A-\lambda_i I & B \end{bmatrix} \begin{bmatrix} V_i \\ q_i \end{bmatrix} = 0 \quad fori = 1 \ldots n$$

(15)

Where V_i is eigenvector and $q_i = kV_i$ in order to satisfy (14) the vector $[V_i^T \quad q_i^T]^T$ must lie in the kernel or null space of the matrix

$$S(\lambda_i) = \begin{bmatrix} A-\lambda_i I & B \end{bmatrix} \qquad (16)$$

The notation ker $S(\lambda_i)$ is used to define the null space which contains all the vectors $[V_i^T \quad q_i^T]^T$ for which (14) is satisfied $q_i = kV_i$ can be used to form the matrix equality:

$$\begin{bmatrix} q_1 & q_2 & \ldots & q_n \end{bmatrix} = \begin{bmatrix} kV_1 & kV_2 & \ldots & kV_n \end{bmatrix} \qquad (17)$$

Since k can be factorized from the right-hand matrix of Eq(17):

$$k = \begin{bmatrix} q_1 & q_2 & \ldots & q_n \end{bmatrix} \begin{bmatrix} V_1 & V_2 & \ldots & V_n \end{bmatrix}^{-1} \qquad (18)$$

4 LQR controller design

This method determines the feedback gain matrix that minimizes J, in order to achieve some compromise between the use of control effort, the magnitude, and the speed of response that will guarantee a stable system.

4.1 control algorithm

For a given system

$$\dot{x} = Ax + Bu \qquad (19)$$

Determine the matrix k of the LQR vector

$$u(t) = -kx(t) \qquad (20)$$

So in order to minimize the cost funcation J

$$J = \int_0^\infty (x^T Qx + u^T Ru)\, dt \qquad (21)$$

Where Q and R are the positive definite ltermition or real symmetric matrix. Thus we get a control law as:

$$u(t) = -kx(t) = -R^{-1} B^T Px(t) \qquad (22)$$

In which P must be determined to solve the Riccati equation as:

$$A^T P + PA - PBR^{-1} B^T P + Q = 0 \qquad (23)$$

5 simulations

This section shows simulation results for STATCOM. The parameters used here are based on those of a practical STATCOM.

5.1 simulation by using pole assignment method

Considerable open loop response, we need to reduce the over shoot of i_d ,settling time of all three states and steady state error of V_{dc} further such that the requirement are satisfied. After trial and error we set the poles on [-2500,-2500,-300].The system response is shown in figure 3,4,5.The overshoot of i_d is reduced to 140(A) and settling time for all three states is reduced to less than 0.017(sec) and V_{dc} is 10000(v). The control effort of D_d and D_q are within [-1,+1].

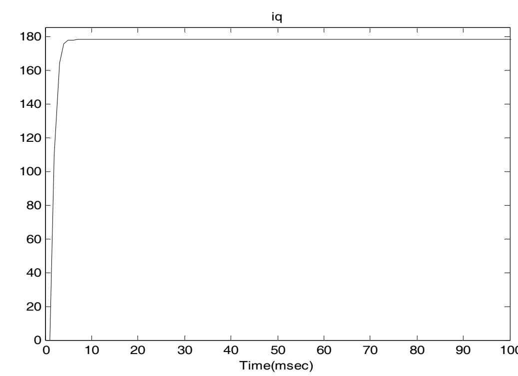

Figure3:i_q response when poles in [-2500,-2500,-300]

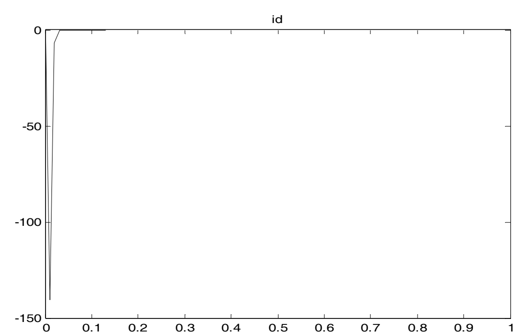

Figure4:id response when poles in [-2500,-2500,-300]

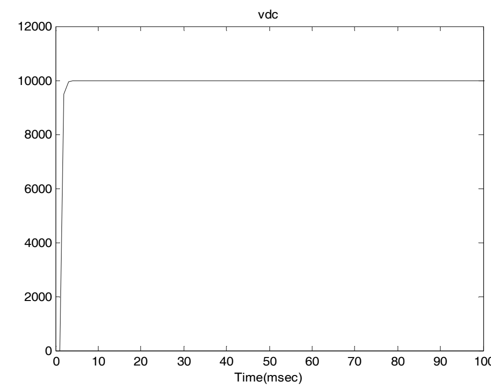

Figure5:v_{dc} response when poles in [-2500,-2500,-300]

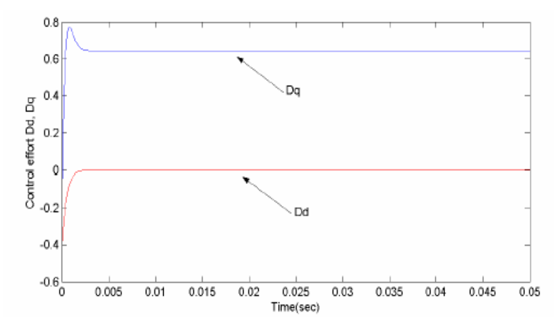

Figure 6:control effort when pole in [-2500,- 2500,-300]

5.2 simulation by using LQR method

In this method, we first select the diagonal elementsof Q and R as diag[Q]=[.005,.005,1500] and diag [R]=[45,100]. The system response is shown in figures 7, 8, 9. We can find that the responses i_d and i_q are perfect and V_{dc} converges to 10000(v) and so all three states are reduced to less than 0.017(sec). The control effort of D_d and D_q are within [-1,+1].

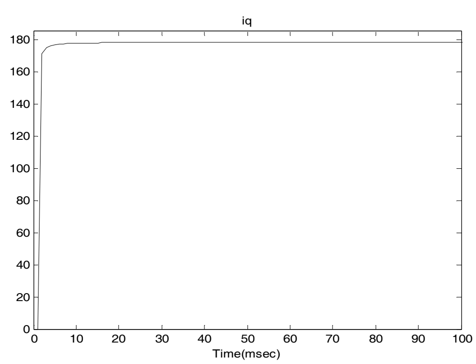

Figure 7:iq response whendiag[Q]=[.005,.005,1500] and diag[R]=[45,100]

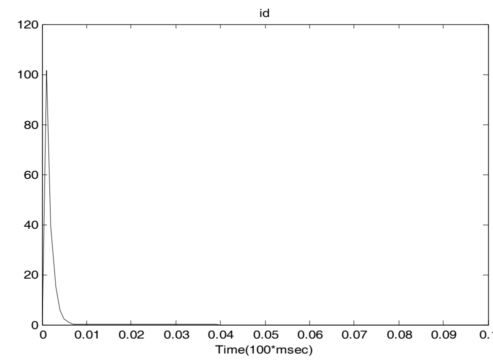

Figure 8:i_d response when diag[Q]=[.005,.005,1500] and diag[R]=[45,100]

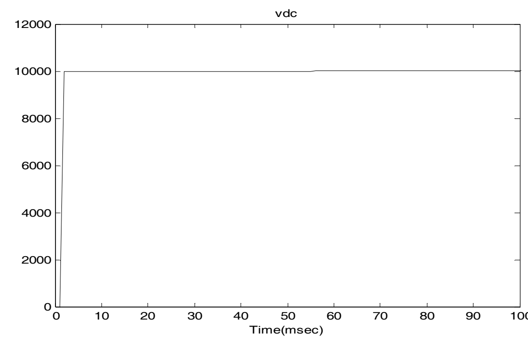

Figure 9:v_{dc} response when diag[Q]=[.005,.005,1500] and diag[R]=[45,100]

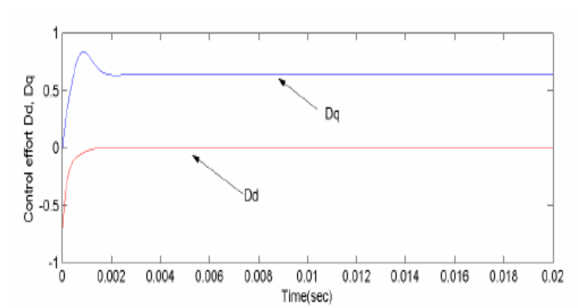

Figure10:control effort when diag[Q]=[.005,.005,1500] and diag[R]=[45,100]

conclusion

we investigated the dynamic model of a typical STATCOM its characteristics show that STATCOM is a nonlinear M.I.M.O system with a control effort saturation requirement. A linearization model method around the operating point can be applied to the nonlinear model to convert it into a linear model. Two kinds of feedback controllers (pole assignment and LQR) are designed. It was found that LQR method is not preferred to pole assignment .However, as a design method the determination of state feedback gains are easier to obtain using LQR method by simulation observations,we can find that STATCOM is a device for reactive power compensation and a good stabilizer.

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