CHAPTER 3

STATE SPACE ANALYSIS OF STATCOM

3.1 INTRODUCTION

The state space model of the STATCOM has been designed using MATLAB/simulink. The design objective is to model and simulate various controllers such as PI, fuzzy and ANNC for STATCOM and also to identify the best controller for the STATCOM by comparing their performances. The reactive power support provided by the STATCOM has been checked by implementing the design in a power system simulation model with various types of loads. The validity and effectiveness of all the control strategies for the STATCOM have been verified by MATLAB simulation results.

3.2 STATE SPACE MODELLING

A power system incorporating FACTS devices is a highly nonlinear system. It is also a non-stationary system, since the power network configuration changes continuously as lines and loads are switched on and off. The dynamic model of the STATCOM is nonlinear and non-constant due to the nature of the inverter switching. Therefore, it is desirable to use a set of simplified state-space model for the STATCOM which is sufficiently accurate to represent the real STATCOM hardware system.
3.3 STATE EQUATION OF STATCOM

The state space equation of the STATCOM is obtained with the equivalent circuit, which is shown in Figure 2.4. By defining a proper synchronous reference frame, the dynamic model of STATCOM can be simplified. The reference frame coordinate is defined and in which the d-axis is always coincident with the instantaneous system voltage vector and the q-axis is in quadrature with it. This transformation of phase variables to instantaneous vectors can be applied to voltages as well as to currents. The state space equation of the STATCOM in phase variable form is given as

\[
\begin{bmatrix}
    i_a' \\
    i_b' \\
    i_c'
\end{bmatrix} =
\begin{bmatrix}
    -\frac{R_s \omega_s}{L_s} & 0 & 0 \\
    0 & -\frac{R_s \omega_s}{L_s} & 0 \\
    0 & 0 & -\frac{R_s \omega_s}{L_s}
\end{bmatrix}
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix} + \frac{\omega_s}{L_s}
\begin{bmatrix}
    e_a' - v_a' \\
    e_b' - v_b' \\
    e_c' - v_c'
\end{bmatrix} (3.1)
\]

The transformation from phase variables to d and q co-ordinates is represented as follows.

\[
\begin{bmatrix}
    i_d \\
    i_q \\
    v_{dc}
\end{bmatrix} =
\begin{bmatrix}
    -\frac{\omega_s R_s}{L_s} & 0 & \frac{k_0 s}{L_s} \cos(\alpha + \theta_i) \\
    -\omega & -\frac{\omega_s R_s}{L_s} & \frac{k_0 s}{L_s} \sin(\alpha + \theta_i) \\
    -\frac{k_0 s}{C} \cos(\alpha + \theta_i) & -\frac{k_0 s}{C} \sin(\alpha + \theta_i) & -\frac{k_0 s}{C_{dcR_{dc}}}
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q \\
    v_{dc}
\end{bmatrix} +
\begin{bmatrix}
    -\frac{\omega}{L_s} \cos \theta_i \\
    -\frac{\omega}{L_s} \sin \theta_i \\
    0
\end{bmatrix} V_i
\]

(3.2)
The general form of the input in state space modeling is given by Equation (3.3) as

\[ \dot{X} = AX + BU \]  

(3.3)

where \( A \) is the state matrix and \( B \) is the input matrix.

### 3.3.1 Output Equation of STATCOM

The general form of output equation in state space modeling is given by Equation (3.4).

\[ Y = CX + DU \]  

(3.4)

where \( C \) is the output matrix and \( D \) represents the direct coupling between input and output (usually zero)

In state space modelling of STATCOM, the state variables \( i_d, i_q \) and \( v_{dc} \) are taken as the output variables. By assuming different values for \( C \) matrix, corresponding variables can be obtained as output as given below.

\[ [C] = [0 \ 1 \ 0] \text{ when the needed output is } i_q. \]

\[ [C] = [0 \ 0 \ 1] \text{ when the needed output is } v_{dc}. \]

The system parameters used to determine the state matrix are given in the following Table 3.1.
Table 3.1 System Parameters

<table>
<thead>
<tr>
<th>FACTS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>$R_{shunt}$</td>
<td>0.6267Ω</td>
</tr>
<tr>
<td>$L_{shunt}$</td>
<td>0.0147H</td>
</tr>
<tr>
<td>$C_{dc}$</td>
<td>940μF</td>
</tr>
</tbody>
</table>

By using the values of $R_{shunt}$, $L_{shunt}$ and $C_{dc}$, which are shunt transformer resistance, inductance and DC capacitance, the state matrix ‘A’ has been formed.

3.4 STATCOM CONTROL

The basic blocks of the state space model consists of plant which has STATCOM and controller. The block diagram representation of the STATCOM control is shown in Figure 3.1.

![Block diagram representation of STATCOM with controller](image-url)
The reference signal can be either capacitor voltage $V_{dc}$ or the reactive current $I_q$. The closed loop operation of STATCOM is first tested with a PI controller. Then based on the error, change in error and output of the PI controller, a Mamdani based fuzzy controller is designed with proper ranges for the linguistic variables namely error, change in error and output. In order to train ANNC, the data are taken from error, previous error and output of PI controller.

### 3.5 PI CONTROLLER

To achieve good control over dc capacitor voltage ($V_{dc}$) and reactive current ($I_q$) injected by STATCOM, a proportional-integral controller is used. Output ($V_{dc}$ or $I_q$) of the STATCOM state space model is compared with the reference input and the error signal is fed to the integral controller. Proportional controller gives $K_p$ times the STATCOM output, which is subtracted from the output of integral controller. The $K_p$ and $K_i$ values are 0.1 and 500 respectively. This controlled input is given to the state space model of the STATCOM in order to track the reference input. The above control action is shown schematically in Figure 3.2

![Figure 3.2 Implementation of PI controller](image)
The reference signal can be of the capacitor voltage $V_{dc}$ or the $I_q$ needed by the load. The reactive power support provided by the STATCOM has been checked by implementing the design with a PI controller in a power system simulation model with various types of loads. Simulink diagram of power system with load for state space analysis is shown in Figure 3.3.

![Simulink diagram of power system with load](image)

**Figure 3.3 Simulink diagram of power system with load**

The reference $I_q$ value is taken from the power system model shown in Figure 3.3. The power system is modelled with a 415V, 50Hz three phase voltage source feeding a load through a transmission line of resistance $R=0.7\Omega$ and inductance $L=1.6\text{mH}$. The load in the power system can be a RL load or RC load and depending upon the type of load, STATCOM injects or absorbs the reactive current $I_q$.

### 3.6 FUZZY CONTROLLER

Fuzzy logic controllers are nonlinear controllers and need no prior plant information. Moreover, they can provide efficient control over a wide range of system operating conditions. They have proved to be very effective,
particularly for complex systems without exact mathematical models, highly nonlinear systems, and systems with significant uncertainties.

Based on the error, change in error and output of the PI controller, a Mamdani based fuzzy controller is designed with proper ranges for the linguistic variables namely error, change in error and output. Mamdani based fuzzy controller is chosen as it has wide spread acceptance, well suited to human input and well suited to mathematical analysis. The maximum value for error and change in error for $V_{dc}$ control is 150V and for $I_q$ control the value is in per unit.

### 3.6.1 Design of Fuzzy Controller

The design of fuzzy controller consists of fuzzification, control rule base establishment, and de-fuzzification.

### 3.6.2 Fuzzification

The fuzzy controller employs two inputs such as the error signal ‘$e$’ and the change in error signal ‘$\Delta e$’. The fuzzy controller has a single output called the control output and is denoted by $u$. The membership functions for error and change in error are shown in Figure 3.4 and 3.5 respectively.
Both the input and output parameters range are normalized between 0 to 1. Since the output ($V_{dc}$ or $I_q$) always lies below the reference value during the simulation, only positive values are taken into account while deciding the range of membership functions for the inputs and output. The membership functions of output $u$ are shown in Figure 3.6.

3.6.3 Control Rule Base

Fuzzy controllers consist of a set of linguistic control rules based on fuzzy implications and the rule of inference. Fuzzy logic systems provide a nonlinear mapping from a set of crisp inputs to a set of crisp outputs using
both intuition and mathematics. In order to do that, each fuzzy logic system is associated with a set of rules, which heuristically define the dynamics of the plant to be controlled. Using Gaussian fuzzifier, a set of crisp inputs are mapped to a fuzzy set. Various rules in the rule base are applied to the fuzzy input data, in order to create a fuzzy output. The fuzzy output is in turn defuzzifier. Table 3.2 shows the control rule base.

**Table 3.2 Rule Base**

<table>
<thead>
<tr>
<th>$\Delta e$</th>
<th>Zero</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero</td>
<td>Large</td>
<td>Large</td>
<td>Medium</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
<td>Large</td>
<td>Large</td>
<td>Medium</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Medium</td>
<td>Large</td>
<td>Large</td>
<td>Medium</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Medium</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Medium</td>
<td>Small</td>
<td>Small</td>
</tr>
</tbody>
</table>

### 3.6.4 Implementation of Fuzzy Controller

Better control over dc capacitor voltage and reactive power support provided by STATCOM is achieved with the implementation of fuzzy controllers. Figure 3.7 shows the implementation of fuzzy logic controller for STATCOM control.
Figure 3.7 Implementation of Fuzzy Controller

The reference signal can be of the capacitor voltage $V_{dc}$ or the $I_q$ needed by the load. The reference $I_q$ value is taken from the power system model. The load in the power system can be a RL load or RC load.

3.7 ANNC

ANNNC has become very popular in many control applications due to their high computation rate and ability to handle nonlinear functions. ANNC is used to reduce the steady state error and settling time. The training patterns for the ANNC are obtained from the error, previous error and output of conventional PI controller and the effectiveness of the proposed ANNC is verified using simulation studies. A conventional controller has heavy computation burden whereas a trained neural network requires less computation time. The ANNC has the ability to generalize and can interpolate in between the training data. This advantage of ANNC makes it universally applicable for many control applications.
The trained neural network outputs the appropriate control signals for achieving the desired response. A two layer feed forward neural network is constructed with two neurons in the input layer and one neuron in the output layer. As the inputs to the ANNC are the error and the previous error, two neurons are used for input layer. The network is trained for the set of inputs and desired outputs. Supervised back propagation training algorithm is used. A back propagation neural network-training algorithm is used with a fixed error goal. The network is trained for an error goal of 0.0005. The values of the trained parameters are $W_{11}=0.2102$, $W_{22}=0.4801$, $W_{12}=0.8011$, $W_{21}=0.4911$, $W_3=0.2210$, $W_4=0.5840$, $b_1=0.4201$, $b_2=0.2912$, $b_3=-0.2122$. Figure 3.8 shows the implementation of ANNC for STATCOM control.
3.8 RESULTS AND ANALYSIS OF THE STATCOM IN STATE SPACE MODELING

3.8.1 $V_{dc}$ CONTROL SIMULATION RESULTS

A state matrix has been formed by taking the parameters from the STATCOM hardware. The $V_{dc}$ control method is adopted and the results are shown in Figure 3.9.

![Figure 3.9](image)

**Figure 3.9** Response of different controllers for $V_{dc}$ Control

In the above Figure 3.9, from the top, the waveforms are $V_{dc}$ref, response of the PI, response of fuzzy and response of ANNC. Reference $V_{dc}$ is taken as 100V during the simulation. The results are shown in Table 3.3.
Table 3.3 Simulation Results of STATCOM for $V_{dc}$ Control

<table>
<thead>
<tr>
<th>S. NO.</th>
<th>Parameters</th>
<th>PI</th>
<th>Fuzzy</th>
<th>ANNC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Peak overshoot (V)</td>
<td>48</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>2.</td>
<td>Settling time (msec)</td>
<td>9</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>3.</td>
<td>Steady state error (V)</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

From Table 3.3, it is found out that the ANNC has less peak overshoot, settling time and steady state error. Hence, it is evident that ANNC is performing better than the other two controllers.

3.8.2 Positive $I_q$ Control Simulation Results

In state space modeling of STATCOM, the $+I_q$ is taken as reference. Figure 3.10 shows the response of the PI, fuzzy and ANNC for positive $I_q$ control in STATCOM.

![Response of different controllers for positive IQ control](image)

In the above Figure 3.10, from the top, the waveforms are $V_{dcref}$, response of the PI, response of fuzzy and response of ANNC. When the load in the power system is inductive in nature, the STATCOM must inject
positive reactive current ($I_q$) in the network. Reference $I_q$ is taken as $+0.5pu$ during the simulation. The results are shown in Table 3.4.

<table>
<thead>
<tr>
<th>S. NO.</th>
<th>Parameters</th>
<th>PI</th>
<th>Fuzzy</th>
<th>ANNC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Peak overshoot (p.u)</td>
<td>0.3</td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>2.</td>
<td>Settling time (msec)</td>
<td>8.5</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>3.</td>
<td>Steady state error (p.u)</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

From Table 3.4, it is found that the ANNC has less peak overshoot, settling time and steady state error. Hence, it is evident that ANNC is performing better than the other two controllers.

3.8.3 Negative $I_q$ Control Simulation Results

In state space modeling of STATCOM, the $-I_q$ is taken as reference. Figure 3.11 shows the response of the PI, fuzzy and ANNC for negative $I_q$ control in STATCOM.

![Figure 3.11 Response of different controllers for negative $I_q$ control](image)

Figure 3.11 Response of different controllers for negative $I_q$ control
When the load in the power system is capacitive in nature, the STATCOM must inject absorb reactive current (I_q) from the network. Reference Iq is taken as -0.5pu during the simulation. The results are shown in Table 3.5.

**Table 3.5 Simulation results of STATCOM for -i_q control**

<table>
<thead>
<tr>
<th>S. NO.</th>
<th>Parameters</th>
<th>PI</th>
<th>Fuzzy</th>
<th>ANNC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Peak overshoot (p.u)</td>
<td>0.35</td>
<td>0.27</td>
<td>0.1</td>
</tr>
<tr>
<td>2.</td>
<td>Settling time (msec)</td>
<td>9</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>3.</td>
<td>Steady state error (p.u)</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

It is found out from Table 3.5 that the ANNC has less peak overshoot, settling time and steady state error. For this control scheme also, ANNC is performing better than the other two controllers.

### 3.9 SUMMARY

A state space model of the STATCOM was designed by taking the parameters from the practical hardware setup. PI, fuzzy and ANN controllers are designed for the STATCOM. The controller performances such as peak overshoot, settling time and steady state error values are noted for the three controllers. These values are compared and it is found that the ANNC is superior in performance to the other three controllers.