REFERENCES


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LIST OF PAPERS


4. Damping of Torsional Oscillations with Coordination of Power System Stabilizer and Static Var Compensator International AMSE Conference, July 4-6, 1994, Lyons, France.

Appendices
APPENDIX - I

SYSTEM DATA

Electrical System

The electrical system considered is 588 MVA generator connected to a 400 KV double line.

(All the following data are in pu on 588 MVA base)

Machine data

\[ x_d = 2.31 \quad x_q = 2.19 \]
\[ x_{sd} = 2.306 \quad x_{shd} = 2.3394 \]
\[ x_{shdq} = 2.1474 \quad x_{shl} = 2.17 \]
\[ x_{shd} = 2.17 \quad x_{skq} = 2.05 \]
\[ x_{shd} = 2.17 \quad x_d'' = 0.21 \]
\[ r_n = 0.00196 \quad r_{id} = 0.00088 \]
\[ r_{id} = 0.01920 \quad r_{sk} = 0.02848 \]

Transformer and Transmission line data

\[ R = 0.0 \quad X = 0.125 \]
\[ R_1 = 0.0228 \quad X_1 = 0.2642 \]
\[ R_2 = 0.0228 \quad X_2 = 0.2642 \]
### Mechanical System

<table>
<thead>
<tr>
<th>Mass</th>
<th>Inertia H(sec)</th>
<th>Shaft sections</th>
<th>Spring constant (pu torque/rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(HP) $H_1$</td>
<td>0.092897</td>
<td>(HP-IP) $K_{12}$</td>
<td>19.303</td>
</tr>
<tr>
<td>(IP) $H_2$</td>
<td>0.155589</td>
<td>(IP-LPA) $K_{23}$</td>
<td>34.929</td>
</tr>
<tr>
<td>(LPA) $H_3$</td>
<td>0.85867</td>
<td>(LPA-LPB) $K_{34}$</td>
<td>52.038</td>
</tr>
<tr>
<td>(LPB) $H_4$</td>
<td>0.884215</td>
<td>(LPB-GEN) $K_{45}$</td>
<td>70.858</td>
</tr>
<tr>
<td>(GEN) $H_5$</td>
<td>0.868495</td>
<td>(GEN-EXC) $K_{56}$</td>
<td>2.822</td>
</tr>
<tr>
<td>(EXC) $H_6$</td>
<td>0.0342165</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mechanical damping $D$ is taken as zero.

### IEEE Type1 Excitation

- $K_A = 150.0$
- $T_A = 0.03\ \text{sec}$
- $K_E = 1.0$
- $T_E = 1.0\ \text{sec}$
- $K_F = 0.02$
- $T_F = 1.0\ \text{sec}$
- $K_R = 1.0$
- $T_R = 0.01\ \text{sec}$
- $A = 0.0039$
- $B = 1.555$
Power system stabilizer (PSS)

The time constants of the PSS with different case studies are given in the following table.

<table>
<thead>
<tr>
<th>Type of control Time constants all are in secs</th>
<th>One pss with generator speed</th>
<th>Modal speed input</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>One PSS</td>
<td>Two PSS</td>
</tr>
<tr>
<td>$T_{p1}$</td>
<td>0.00439</td>
<td>0.00439</td>
</tr>
<tr>
<td>$T_{p2}$</td>
<td>0.3475</td>
<td>0.3475</td>
</tr>
<tr>
<td>$T_{p3}$</td>
<td>0.0075</td>
<td>0.0075</td>
</tr>
<tr>
<td>$T_{p4}$</td>
<td>0.009</td>
<td>0.009</td>
</tr>
<tr>
<td>$T_{p5}$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$T_{p6}$</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>$T_{p7}$</td>
<td>0.001</td>
<td>0.00439</td>
</tr>
<tr>
<td>$T_{p8}$</td>
<td>0.3475</td>
<td>0.3475</td>
</tr>
<tr>
<td>$T_{p9}$</td>
<td>0.0075</td>
<td>0.0075</td>
</tr>
<tr>
<td>$T_{p10}$</td>
<td>0.009</td>
<td>0.009</td>
</tr>
<tr>
<td>$T_{p11}$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$T_{p12}$</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Gains of PSS

1. One PSS with generator speed deviation input $K_{ps} = 2.2$ or $10.0$
   - $K_{ps1} = 5.5$
   - $K_{ps2} = -2.5$

2. One PSS with modal speed deviation input
   - $K_{ps1} = 5.5$
   - $K_{ps2} = 12.0$

3. Two PSS with modal speed deviation input
   - $K_{ps1} = 20.0$
   - $K_{ps2} = -15.0$
   - $K_{ps3} = 18.0$
   - $K_{ps4} = -20.0$

SVC data

- $X = 12.0$
- $\alpha = 2.0 \text{ rad}$
- $\alpha = 130.0$
- $c = 1000.0$
- $d = 1050.0$
- $e = 10.0$
- $f = 160.0$
- $T_m = 0.451 \text{ sec}$
- $T_e = 0.002255 \text{ sec}$

Proportional control gain $K_w = 65.0$

SVC auxiliary control with filter

- $T_{s1} = 1.0 \text{ sec}$
- $T_{s2} = 0.03$

Proportional gain $K_p = 12.0$

Proportional + derivative gains $K_p = 10.0$, $K_d = 0.5$

PID control gains $K_p = 15.0$, $K_i = 0.5$, $K_d = 4.0$

(To convert the quantities in sec to pu they should be multiplied by base angular speed 377 rad/sec).
Read Conditions:
Mech, Exciter, PSS, Ipstyp, Isvc, Isvctyp, Iqata
Call all the required data subroutines.
Read the initial, incremental and maximum values of
coordinate C:

CALL INIT.

Composition of common elements of
P, Q, R matrices

CALL GEN.

CALL MATH.

Formation of
P, Q, R matrices

CALL MAINT.

Partition P, Q, R matrices such that
P=P(x, y, z, t); Q=x, y, z, t; R=x, y, z, t

Yes

CALL INC.

CALL PSS.

CALL PSE.

CALL ASSEM.

[In current excitation system and PSS
with electromagnetic system formation
of A matrix]

CALL SEQ.

Print error values

If real part of error value > 0

System is stable

PERCENT = PERCENT + PERCENT

PERCENT < PERCENT

STOP
APPENDIX - II

CALCULATION OF INITIAL CONDITIONS

From the data, the initial conditions of all the state variables are calculated using the following procedure. Steady state values are specified in terms of the generator terminal conditions viz., power generated $P_g$, power factor $P_f$ and the terminal voltage $v_t$. The electrical network is as shown in fig.3.1. The calculation of initial conditions for the system having SVC is different to that of the system without SVC.

II.1 Initial conditions without SVC

The phasor diagram is as shown in fig. II.1. The total impedance between generator terminal and the infinite bus is given by

$$Z = R + jX + \frac{[R_g + j(X_g - X_o)]}{[R_t + jX_t + R_g + j(X_g - X_o)]}$$  \hspace{1cm} (II.1)

The generator terminal current which is also equal to the line current is given by

$$|I_t| = \frac{P_g}{|v_t|.P_f}$$  \hspace{1cm} (II.2)

Resolving $I_t$ into components with reference to $v_t$ we get,

$$I_t = I_r + jI_x$$  \hspace{1cm} (II.3)

Where

$$I_r = |I_t|.P_f$$

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\[ I_x = \left| I_1 \right| \sin(\phi) \]
\[ \phi = \cos^{-1}(PQ) \]

The voltage at the infinite bus is given by

\[ v_0 = v_r - Z (I_r + jI_g) \]
\[ = \left| v_0 \right| \angle \beta_1 \]  

(II.4)  

(II.5)

Since the infinite bus voltage is taken as the reference axis the negative of the angle \( \beta_1 \) is the angle by which the terminal voltage \( v_r \) leads the infinite bus voltage. Hence with reference to \( v_0 \), the terminal voltage is \( v_r \angle \Theta \) where \( \beta = -\beta_1 \).

The current at the generator terminals, \( I_r \) is now calculated as

\[ I_r = \frac{v_r \angle \beta - v_0 \angle \Theta}{Z} = \left| I_r \right| \angle \Theta \]  

(II.6)

Where \( \Theta \) is the angle between \( v_0 \) and \( I_r \). The currents in the parallel branches are calculated as

\[ I_1 = \frac{Z_2 I_1}{Z_1 + Z_2} = \left| I_1 \right| \angle \Theta_2 \]  

(II.7)

\[ I_2 = \frac{Z_1 I_1}{Z_1 + Z_2} = \left| I_2 \right| \angle \Theta_2 \]  

(II.8)

where \( Z_1 = R_1 + jX_1 \), \( Z_2 = R_2 + j(X_2 - X_0) \)
The angle $\delta_1$ can be obtained by calculating the voltage $E_{61}$ which lies along the quadrature axis.

$$| E_{61} | \angle \delta_1 = | v_1 | \angle \beta + (v_n + jx_q) | I_1 | \angle \Theta$$  \hspace{1cm} (II.9)

From the vector diagram the angle between $E_{60}$ and $v_1$ is

$$\delta = \delta_1 - \beta$$  \hspace{1cm} (II.10)

The voltages and currents along the $d$ and $q$ axes are calculated by using the following formulae which are obtained from the phasor diagram shown in fig. II.1.

$$v_{od} = | v_0 | \sin \delta_1$$  \hspace{1cm} (II.11)

$$v_{oq} = | v_0 | \cos \delta_1$$  \hspace{1cm} (II.12)

$$v_d = | v_1 | \sin \delta$$  \hspace{1cm} (II.13)

$$v_q = | v_1 | \cos \delta$$  \hspace{1cm} (II.14)

$$i_d = | I_1 | \cos (\pi/2 - (\delta_1 - \Theta))$$  \hspace{1cm} (II.15)

$$i_q = | I_1 | \sin (\pi/2 - (\delta_1 - \Theta))$$  \hspace{1cm} (II.16)

$$i_{d1} = | I_1 | \cos (\pi/2 - (\delta_1 - \Theta_1))$$  \hspace{1cm} (II.17)

$$i_{q1} = | I_1 | \sin (\pi/2 - (\delta_1 - \Theta_1))$$  \hspace{1cm} (II.18)

$$i_{d2} = | I_2 | \cos (\pi/2 - (\delta_1 - \Theta_2))$$  \hspace{1cm} (II.19)

$$i_{q2} = | I_2 | \sin (\pi/2 - (\delta_1 - \Theta_2))$$  \hspace{1cm} (II.20)

Voltages across the capacitor are given by

$$v_{ei} = X_c i_{q2}$$  \hspace{1cm} (II.21)

$$v_{ec} = -X_c i_{d2}$$  \hspace{1cm} (II.22)
The open circuit voltage $E_{id}$ which is proportional to the field current $i_{id}$ at steady state is given by

$$E_{id} = v_d + r_d i_d + x_d i_d$$  \hspace{1cm} \text{(II.23)}

The field current is given by

$$i_{id} = \frac{E_{id}}{x_{aid}}$$  \hspace{1cm} \text{(II.24)}

$i_{ad}$, $i_{aq}$ are assumed to be zero.

The flux linkages are calculated by using the following formulae.

$$\psi_d = -x_d i_d + x_{aid} i_{ad} + x_{aid} i_{bd}$$  \hspace{1cm} \text{(II.25)}

$$\psi_q = -x_q i_q + x_{aq} i_{aq}$$  \hspace{1cm} \text{(II.26)}

$$\psi_{id} = -x_{aid} i_d + x_{aid} i_{ad} + x_{aid} i_{bd}$$  \hspace{1cm} \text{(II.27)}

$$\psi_{id} = -x_{akd} i_d + x_{akd} i_{ad} + x_{akd} i_{bd}$$  \hspace{1cm} \text{(II.28)}

$$\psi_{iq} = -x_{akq} i_q + x_{akq} i_{aq}$$  \hspace{1cm} \text{(II.29)}

The electrical torque $T_U$ and power at the infinite bus are calculated using

$$T_U = \psi_q i_d - \psi_d i_q$$  \hspace{1cm} \text{(II.30)}

$$P_O = v_d i_d + v_q i_q$$  \hspace{1cm} \text{(II.31)}
II.2 Initial conditions with SVC

Since the SVC is connected at the generator terminals, the line current is different, from the terminal current, and also the power factor is between the line current and the terminal voltage. The phasor diagram is as shown in the fig. II.2.

From the equivalent model of SVC we write

\[ X_{Ct} = \left[ \frac{2\alpha - \sin 2\alpha}{\pi} - 1.0 \right] \]  \hspace{1cm} (II.32)

Where \( \alpha \) is the firing angle of thyristor in radians. The susceptance of the SVC, \( B_{svc} \) is calculated as

\[ B_{svc} = \frac{X_{Ct} - 1}{X_s} \]  \hspace{1cm} (II.33)

The current through SVC can be obtained as

\[ I_s = |I_s| \angle \Theta_s = B_{svc} \cdot V_t \]  \hspace{1cm} (II.34)

The line current is given by

\[ |I_L| = \frac{P_o}{|V_t| \cdot Pf} \]  \hspace{1cm} (II.35)

resolving \( I_L \) into components with reference to \( V_t \), we write

\[ I_L = I_r + jI_x \]  \hspace{1cm} (II.36)

where

\[ I_r = |I_L| \cdot Pf \]
\[ I_x = - |I_L| \sin (\Phi) \]
\[ \Phi = \cos^{-1} (Pf) \]
The voltage at the infinite bus is calculated as

\[ V_0 = v_i - Z(I_i + jI_q) \]  
\[ v_0 = |v_0| \angle \beta_i \] (II.37)

Since the infinite bus is taken as reference, the negative of the angle \( \beta_i \) is the angle by which the terminal voltage \( v_i \) leads the infinite bus voltage \( v_0 \).

The currents in the parallel branches are calculated as

\[ I_1 = \frac{Z_i \cdot I_i}{Z_1 + Z_2} = |I_1| \angle \Theta_1 \] (II.38)

\[ I_2 = \frac{Z_i \cdot I_i}{Z_1 + Z_2} = |I_2| \angle \Theta_2 \] (II.39)

where \( Z_i = R_i + jX_i \), \( Z_2 = R_2 + j(x_{eq} - x_C) \)

The generator terminal current is obtained as

\[ I_1 = I_{i_1} + I_s \] (II.40)

To get the d and q components of the currents and voltages equations (II.9) to (II.30) are used. SVC currents along d and q axes are calculated by using

\[ i_{sd} = |I_1| \cos (\pi/2 - (\delta_i - \Theta)) \] (II.41)

\[ i_{sq} = |I_1| \sin (\pi/2 - (\delta_i - \Theta)) \] (II.42)

The infinite bus power can be calculated by using

\[ P_0 = v_{od} (i_d - i_{sd}) + v_{oq} (i_q - i_{sq}) \] (II.43)
Table II.1 Initial conditions without SVC

\[ \begin{align*}
\nu_d &= 0.7096 & \nu_d &= 0.9458 & \nu_d &= 0.7053 \\
\nu_q &= 0.7046 & \nu_q &= 0.3249 & \nu_q &= -0.7114 \\
E_{fu} &= 2.8900 & E_{fu} &= 1.3318 & E_{fu} &= 1.0118 \\
\nu_{f1} &= 0.9020 & \nu_{f1} &= 0.0000 & \nu_{f1} &= 0.8377 \\
E_{k1} &= 0.0000 & E_{k1} &= 0.0000 & E_{k1} &= -0.6666
\end{align*} \]

| Percent | \(X_e\) | \(\delta_i\) | \(|v_0|\) | \(v_{ce}\) | \(v_{sq}\) |
|---------|--------|-------------|----------|----------|----------|
| 0.0     | .0000  | 59.3712     | .9064    | .0000    | -.0000   |
| 5.0     | .0132  | 59.4614     | .9071    | .0022    | -.0064   |
| 10.0    | .0264  | 59.2407     | .9078    | .0046    | -.0131   |
| 15.0    | .0396  | 59.0084     | .9085    | .0071    | -.0202   |
| 20.0    | .0528  | 58.7635     | .9093    | .0098    | -.0276   |
| 25.0    | .0661  | 58.5048     | .9101    | .0127    | -.0355   |
| 30.0    | .0793  | 58.2813     | .9109    | .0158    | -.0438   |
| 35.0    | .0925  | 57.9417     | .9118    | .0191    | -.0526   |
| 40.0    | .1057  | 57.6343     | .9128    | .0227    | -.0619   |
| 45.0    | .1189  | 57.3077     | .9138    | .0266    | -.0717   |
| 50.0    | .1321  | 56.9698     | .9149    | .0309    | -.0822   |
| 55.0    | .1453  | 56.5887     | .9160    | .0355    | -.0934   |
| 60.0    | .1585  | 56.1918     | .9172    | .0405    | -.1063   |
| 65.0    | .1717  | 55.7687     | .9186    | .0440    | -.1180   |
| 70.0    | .1849  | 55.3094     | .9198    | .0521    | -.1316   |
| 75.0    | .1982  | 54.8171     | .9213    | .0588    | -.1463   |
| 80.0    | .2114  | 54.2853     | .9228    | .0681    | -.1620   |
| 85.0    | .2246  | 53.7089     | .9245    | .0744    | -.1789   |
| 90.0    | .2378  | 53.0823     | .9263    | .0836    | -.1974   |
| 95.0    | .2510  | 52.3986     | .9282    | .0939    | -.2173   |
| 100.0   | .2642  | 51.6496     | .9303    | .1055    | -.2391   |

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Table II.2 Initial conditions with SVC

\[
\begin{align*}
\psi_{d} &= 0.6085 \quad \psi_{q} = 0.7941 \\
\psi_{d} &= 0.7936 \quad \psi_{q} = -0.6107 \\
\psi_{d} &= 0.3707 \quad \psi_{q} = 1.1615 \\
\psi_{d} &= 0.9026 \quad \psi_{q} = 0.9503 \\
\psi_{d} &= 0.0000 \quad \psi_{q} = -0.5716
\end{align*}
\]

| Percent | \(X_c\) | \(\delta_i\) | \(|V_o|\) | \(V_{cd}\) | \(V_{eq}\) |
|---------|--------|-------------|---------|---------|---------|
| 0.0     | 0.0000 | 52.8106     | .8463   | .0000   | -.0000  |
| 5.0     | 0.0132 | 52.5703     | .8477   | .0021   | -.0073  |
| 10.0    | 0.0264 | 52.3190     | .8492   | .0043   | -.0150  |
| 15.0    | 0.0396 | 52.0541     | .8507   | .0067   | -.0231  |
| 20.0    | 0.0528 | 51.7751     | .8523   | .0092   | -.0317  |
| 25.0    | 0.0661 | 51.4808     | .8541   | .0119   | -.0407  |
| 30.0    | 0.0793 | 51.1701     | .8559   | .0149   | -.0502  |
| 35.0    | 0.0926 | 50.8413     | .8578   | .0181   | -.0603  |
| 40.0    | 0.1057 | 50.4930     | .8599   | .0215   | -.0710  |
| 45.0    | 0.1189 | 50.1234     | .8621   | .0253   | -.0823  |
| 50.0    | 0.1321 | 49.7504     | .8644   | .0293   | -.0943  |
| 55.0    | 0.1453 | 49.3117     | .8663   | .0338   | -.1072  |
| 60.0    | 0.1585 | 48.8647     | .8695   | .0387   | -.1209  |
| 65.0    | 0.1717 | 48.3866     | .8723   | .0440   | -.1365  |
| 70.0    | 0.1849 | 47.8739     | .8754   | .0499   | -.1512  |
| 75.0    | 0.1982 | 47.3228     | .8786   | .0565   | -.1681  |
| 80.0    | 0.2114 | 46.7287     | .8822   | .0638   | -.1862  |
| 85.0    | 0.2246 | 46.0865     | .8860   | .0719   | -.2059  |
| 90.0    | 0.2378 | 45.3901     | .8901   | .0810   | -.2271  |
| 95.0    | 0.2510 | 44.6323     | .8946   | .0913   | -.2502  |
| 100.0   | 0.2642 | 43.8049     | .8996   | .1030   | -.2753  |
Fig. II.1: Phasor Diagram without SVC

Fig. II.2: Phasor Diagram with SVC
APPENDIX III

MODES OF OSCILLATION AND MODE SHAPES

Consider an unforced, undamped mechanical system as shown in the fig.3.3.

The system can be described by a set of second order differential equations that can be written in matrix form as follows. (all quantities are in per unit except time in seconds and \( \delta \) in radians).

\[
\frac{1}{\omega_o} \begin{bmatrix} \vdots \end{bmatrix} [H] [\delta] + [K] [\delta] = 0 \quad (III.1)
\]

Where \([H] = \text{diag} [2H_1, 2H_2, 2H_3, 2H_4, 2H_5, 2H_6] \) \hspace{1cm} (III.2)

\([\delta] = \begin{bmatrix} \delta_1 & \delta_2 & \delta_3 & \delta_4 & \delta_5 \end{bmatrix} \) \hspace{1cm} (III.3)

\[
[K] = \begin{bmatrix}
K_{12} & -K_{13} \\
-K_{12} & K_{13}+K_{23} & -K_{23} \\
-K_{23} & K_{23}+K_{34} & -K_{34} \\
-K_{34} & K_{34}+K_{45} & -K_{45} \\
-K_{45} & K_{45}+K_{56} & -K_{56} \\
-K_{56} & K_{56} & K_{66}
\end{bmatrix}
\]

At resonance all masses oscillate at the same frequency \( \omega_o \), such that

\[
\delta_i = X_i \sin(\omega_o t + \alpha), \quad i = 1, 2, ..., 6 \quad (III.2)
\]

substituting equation (III.2) in (III.1) we get
\[
\begin{align*}
\begin{bmatrix} (\omega_n^2/\omega_0) [H] \end{bmatrix} \mathbf{X} &= \begin{bmatrix} [K] \end{bmatrix} \mathbf{X} = 0 \text{ or} \\
[M] \mathbf{X} &= (\omega_n^2/\omega_0) \mathbf{X} = \lambda_n \mathbf{X} \quad \text{(III.3)}
\end{align*}
\]

Where \([M] = [H]^{-1} [K]\) and \(\lambda_n = (\omega_n^2/\omega_0)\)

\[\text{i.e., } \omega_n = \sqrt{\lambda_n \omega_0} = 0, 1, \ldots, 5 \quad \text{(III.4)}\]

To each \(\omega_n\) corresponds an eigen vector \(\mathbf{Q}_n\). A transformation matrix \([\mathbf{Q}]\)

is formed as follows.

\[
[\mathbf{Q}] = [\mathbf{Q}_0 \mathbf{Q}_1 \mathbf{Q}_2 \mathbf{Q}_3 \mathbf{Q}_4 \mathbf{Q}_5 \mathbf{Q}_6]
\]

The values of \(\omega_n\) and the matrix \(\mathbf{Q}\) for the data used in this study are given below.

<table>
<thead>
<tr>
<th>mode (m)</th>
<th>(\omega_n) (rad)</th>
<th>frequency Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>98.72</td>
<td>15.71</td>
</tr>
<tr>
<td>2</td>
<td>127.00</td>
<td>20.21</td>
</tr>
<tr>
<td>3</td>
<td>160.62</td>
<td>28.55</td>
</tr>
<tr>
<td>4</td>
<td>202.85</td>
<td>32.28</td>
</tr>
<tr>
<td>5</td>
<td>298.18</td>
<td>47.48</td>
</tr>
</tbody>
</table>

\[
[\mathbf{Q}] = \begin{bmatrix}
1 & -0.7777 & 0.1099 & 1 & 0.8638 & -0.7874 \\
1 & -0.5837 & 0.0646 & 0.3422 & -0.0437 & 1 \\
1 & -0.3424 & 0.015 & -0.2297 & -0.5027 & -0.1133 \\
1 & 0.1117 & -0.0395 & -0.0654 & 1 & 0.0211 \\
1 & 0.3731 & -0.0374 & 0.166 & -0.6205 & -0.0045 \\
1 & 1 & 1 & -0.2525 & 0.3768 & 0.0009 \\
\end{bmatrix}
\]

Each column of the matrix \([\mathbf{Q}]\) corresponds to a mode shape shown in fig. 3.4.