Journal of ELECTRICAL ENGINEERING, VOL. 56, NO. 11-12, 2005, 290–297

OPTIMAL POLE SHIFT CONTROL IN APPLICATION TO A HYDRO POWER PLANT

Nand Kishor * — **R. P. Saini** * — **S. P. Singh** **

This paper presents a design technique to control a low-head hydro power plant connected as a single machine to an infinite bus (SMIB) system. A state-space model with two-input and two-output variables is considered. The control action is performed through the excitation and governor subsystems. The approach used is based on optimal pole shift theory. The solution to optimal control is achieved without solving any non-linear algebraic Riccati equation. The discussed technique offers satisfactory damping effects on speed and load angle oscillations. It is observed that the system's satisfactory response remains unchanged for any variation in a plant parameter that may occur due to change in operating conditions of a plant.

K e y w o r d s: optimal pole shift, single machine infinite bus, hydro plant, gain matrix

1 INTRODUCTION

Power plant oscillations generally occur due to the lack of damping torque at the generator rotor. The rotor oscillation causes the oscillation of power system variables (bus voltage, bus frequency, transmission line active and reactive power, *etc*). Power system oscillations are usually in the range between 0.1 Hz to 2 Hz.

In the classical design of controller for hydro-turbine-generator unit, the speed control and the excitation control were considered as two separate entities, which are independent of each other [1]. The reason lies due to the fact that the operation of speed loop is slower than excitation loop. In recent years digital adaptive control techniques have offered an enhanced efficiency in the identification and control. The mutual coordination between the governor and exciter control loops helps in obtaining better damping of transients and wider stability margins.

There has been some reported literature [2-7] in which pole shift approach has been applied in power system applications (Power system stabilizer) and in the design of adaptive governor for synchronous operation of a hydro-electric unit [8]. A generalized multivariable pole shifting adaptive control algorithm is presented in [2]. The technique provides on-line self-searching pole shifting factor to determine the excitation control limits over a wide operating range. An adaptive self-optimizing pole shift technique in the design of power system stabilizer is discussed in [3]. The control algorithm presented is based on combined essences of minimum variance and pole assignment. Further Chen *et al*. [4] have described an adaptive power system stabilizer. A recursive least square method with a varying forgetting factor is used and the degree of shift is determined by a pole shift factor. A state-feedback law based on pole shift approach is presented in [5]. The feedback gains and system parameters can be determined easily, as gains are linear functions of the pole shift factor. Radial basis function identifier with pole shift controller is applied for the design of power system stabilizer in [6]. Abdelazim and Malik [7] have presented Takagi-Sugeno (TS) fuzzy system to identify a synchronous machine model and the pole shift control is applied to calculate the control signal. The identifier is a NARMAX model and hence more suitable to represent the non-linear nature of power systems. A robust adaptive controller design using pole shift and parameter space method for governing of hydro turbine is described in [8].

Recently the pole shift control scheme [9,10] has been demonstrated for the power system stabilizer and hydropower plant control applications. This technique does not need the solution of non-linear algebraic Riccati equation and is easy to solve.

In the present paper, the possibility to obtain a coordinated control of exciter and governor in a low head hydro power plant is presented. The control scheme based on optimal pole shift is employed. The method is based on mirror image property [11]. The optimal pole shift technique yields a solution, which is optimal with respect to a quadratic performance index [11]. Its solution can be easily found without solving any non-linear algebraic Riccati equation. It requires only a first or a second order Lyapunov equation to be solved for shifting a real or a complex pole, respectively. The analysis is carried out to study the effectiveness of this technique under various load disturbances and operating conditions.

2 SYSTEM DESCRIPTION AND MODELLING

In the present paper single Kaplan turbine-generator with exciter and governor in a low-hydro power plant connected to local load and an infinite bus as shown in Fig. 1, is considered for the study. The linear model of SMIB system characterizes system oscillations accurately. This is due to the fact that system oscillations depend on the operating point of the power plant rather than the location and magnitude of the applied disturbance. The size and complexity of linear power plant model requires the

* Alternate Hydro Energy Centre, Indian Institute of Technology, Roorkee, Roorkee-247667, India; ** Department of Electrical Engineering, Indian Institute of Technology, Roorkee, Roorkee-247667, India

ISSN 1335-3632

use of state-space models. The usual approach to analyze these systems consists of computing the eigenvalues and eigenvectors of the state matrix.

The dual regulation of hydro-turbine is incorporated through the operation of both wicket gate and runner blade. The hydraulic flow in the penstock is modelled with the assumption of inelastic water column effect. The stiff water hammer equation can be expressed as [12]:

$$\frac{\mathrm{d}h}{\mathrm{d}t} = -T_w \frac{\mathrm{d}q}{\mathrm{d}t} \tag{1}$$

The turbine flow q and torque m in case of Kaplan turbine are non-linear functions of head h, wicket gate opening z, machine speed w and runner blade position θ.

For a given reference operating point, the partial derivative relationship between these variables is given as [13]:

$$\begin{aligned} q &= \frac{\delta q}{\delta h}h + \frac{\delta q}{\delta z}z + \frac{\delta q}{\delta w}w + \frac{\delta q}{\delta \theta}\theta \\ &= T_1 h + T_2 z + T_3 w + T_4 \theta \end{aligned} \tag{2}$$

$$\begin{aligned} m &= \frac{\delta m}{\delta h}h + \frac{\delta m}{\delta z}z + \frac{\delta m}{\delta w}w + \frac{\delta m}{\delta \theta}\theta \\ &= T_5 h + T_6 z + T_7 w + T_8 \theta \end{aligned} \tag{3}$$

$$\frac{\mathrm{d}q}{\mathrm{d}t} = \frac{1}{T_w T_1}\left[T_3 w + T_2 z - q + T_4 \theta\right] \tag{4}$$

The operation of Kaplan turbine involves control of the wicket gate and the runner blade position in order to regulate the water flow to the hydro-turbine. The corresponding servomotor equations are described as [13]:

$$\frac{\mathrm{d}z}{\mathrm{d}t} = (u_{gov} - z)/T_{gv}, \quad \frac{\mathrm{d}\theta}{\mathrm{d}t} = (u_{gov} - \theta)/T_{rb} \tag{5,6}$$

where T_{gv} and T_{rb} are the wicket gate and runner blade servomotor constants, respectively.

A third order synchronous generator model is described by the following set of differential and algebraic equations [1]:

$$T_a \frac{dw}{dt} = m - m_l - Dw, \quad \frac{d\delta_l}{dt} = w_0 w \tag{7,8}$$

$$\frac{\mathrm{d}e'_q}{\mathrm{d}t} = \frac{1}{\tau'_{d0}}\left[E_{FD} - \frac{1}{K_3}e'_q - K_4\delta_l\right] \tag{9}$$

$$m_l = K_1\delta_l + K_2 e'_q \tag{10}$$

Expressing the exciter equations as [14]:

$$\frac{\mathrm{d}E_{FD}}{\mathrm{d}t} = \frac{1}{T_E}\left[V_a - K_E E_{FD}\right] \tag{11}$$

$$\begin{aligned} &\frac{\mathrm{d}V_a}{\mathrm{d}t} = \frac{1}{T_A}\left[K_A V_{ref} + K_A u_{ex} - K_A V_t - K_A V_f - V_a\right] \\ &V_t = K_5\delta_l + K_6 e'_q \end{aligned} \tag{12}$$

$$\frac{\mathrm{d}V_f}{\mathrm{d}t} = \frac{1}{T_F}\left[\frac{K_F K_E}{T_E}E_{FD} + \frac{K_F}{T_E}V_a - V_f\right] \tag{13}$$

The dynamic characteristics of the system are expressed in terms of constants K_1–K_6. These constants except K_3 depend upon the actual real and reactive power loading as well as the excitation levels in the machine. The constant K_3 is an impedance factor that takes into account the loading effect of the external impedance.

The SMIB system represented in state space form is given by:

$$\dot{x}(t) = A\,x(t) + B\,u(t) \tag{14}$$

where the system state vector x and the system control vector u are defined as follows:

$$x(t) = [w, \delta, e'_q, E_{FD}, V_a, V_f, q, z, \theta]^T$$

$$u(t) = [u_{ex}, u_{gov}]^T$$

with u_{ex} being the exciter voltage signal and u_{gov} governor gate position. Using the following abbreviations

$$K_7 = T_7 - (T_3T_5)T_1 - D,$$

$$K_8 = T_6 - (T_5T_2)/T_1, \quad K_9 = T_8 - (T_5T_4)/T_1,$$

matrices A and B in (14) are expressed as:

$$A = \begin{bmatrix} \frac{K_7}{T_a} & -\frac{K_1}{T_a} & -\frac{K_2}{T_a} & 0 & 0 & 0 & \frac{T_5T_1}{T_a} & \frac{K_8}{T_a} & \frac{K_9}{T_a} \\ w_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_4}{\tau'_{d0}} & -\frac{1}{K_3\tau'_{d0}} & \frac{1}{\tau'_{d0}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{K_E}{T_E} & \frac{1}{T_E} & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_AK_5}{T_A} & -\frac{K_AK_6}{T_A} & 0 & -\frac{1}{T_A} & -\frac{K_A}{T_A} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{K_FK_E}{T_FT_E} & \frac{K_F}{T_FT_E} & -\frac{1}{T_F} & 0 & 0 & 0 \\ \frac{T_3}{T_wT_1} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_wT_1} & \frac{T_2}{T_wT_1} & \frac{T_4}{T_wT_1} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{gv}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{rb}} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{K_A}{T_A} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{gv}} & \frac{1}{T_{rb}} \end{bmatrix}^T$$

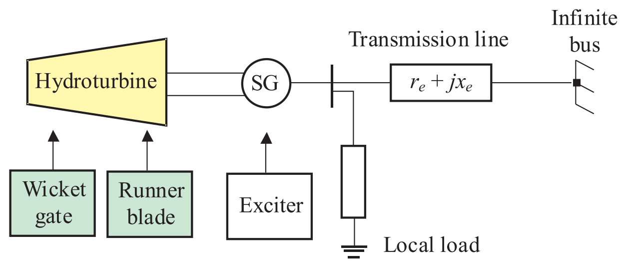

Fig. 1. A low-head hydro power plant connected as SMIB system

3 OPTIMAL POLE SHIFT

In the present work, the optimal pole shift approach suggested by Amin [11] has been used. The method does not require the solution of non-linear algebraic Riccati equation. A first-order or a second-order linear Lyapunov equation is to be solved for shifting one real or two complex conjugate poles, respectively. To shift the complex conjugate poles to a desired location only real part of the open-loop complex conjugate poles are shifted keeping the magnitude of imaginary parts preserved. The shift of real/complex conjugate poles is achieved by an optimal feedback control law with respect to a quadratic performance index [11]. Consider a completely controllable linear time-invariant multivariable system represented as:

$$\dot{x}(t) = A\,x(t) + B\,u(t) \tag{15}$$

where the dimensions of the state vector x and the control vector u are $(n \times 1)$ and $(m \times 1)$, respectively. A and B are constant plant matrices of appropriate dimensions. When a feedback control law:

$$u = -Kx \tag{16}$$

is applied to (15), a closed-loop system is derived in the form:

$$\dot{x} = A_c x \tag{17}$$

where $A_c = A - BK$. With a given controllable pair (A, B) , and if A is a non-singular matrix, then for the following algebraic equation

$$PA + A^T P - PBB^T P = 0 \tag{18}$$

there exists a positive semi-definite real symmetric solution P that satisfies $\mathrm{Re}(S_i) < 0$ and $S_i^2 = \lambda_i^2$ with $i = 1, 2, .., n$ where λ_i and S_i are the open-loop and closed-loop poles with the feedback gain matrix $K = B^T P$.

For any S_i and λ_i which satisfy the optimality condition, the quantities $\alpha_i = \frac{-(\mathrm{Re}(S_i)+\mathrm{Re}(\lambda_i))}{2}$ and $(\alpha_i + \mathrm{Re}(\lambda_i))$ are positive.

Let α be a positive real constant scalar. Then for the following matrix algebraic equation:

$$P(A + \alpha I) + (A^T + \alpha I)P - PBR^{-1}B^T P = 0 \tag{19}$$

there exists a positive semi-definite real symmetric solution P satisfying: $\mathrm{Re}(S_i) \le -\alpha$ and $(S_i + \alpha)^2 = (\lambda_i + \alpha)^2$ with $i = 1, 2, \dots, n$ and

$$K = R^{-1} B^T P \tag{20}$$

where R is a positive definite symmetric matrix for the given controllable pair (A, B).

Also the feedback control law $u = -Kx$ minimizes the following quadratic performance index

$$J = \int_0^\infty (x^T Q x + u^T R u)dt \tag{21}$$

with $Q = 2\alpha P$. The theory of one real pole shift, a complex pole shift and several poles shift is given in Appendix A.

4 SIMULATION RESULTS AND DISCUSSION

The hydro plant connected to infinite bus with local load at generator terminal is represented as two-input and two-output system. The two inputs are exciter and gate-blade position and the two outputs are speed and load angle. The parameters considered in the study for the power plant are given in Appendix B. The open loop eigenvalues (λ_i) determined from (14) at heavy load ($P_e = 1.0$ pu, $Q_e = 0.62$ pu) and light load ($P_e = 0.2$ pu, $Q_e = 0.0$ pu) conditions are given in Table 1.

The time domain simulations are performed with (i) step signal and (ii) exponential signal. Due to limited space in the paper, simulation results at operating point: $P_e = 1.0$ pu, $Q_e = 0.62$ pu are presented here. The output response of the plant without controller is simulated for load disturbance: 0.02 $pu$and 0.05 pustep increment and 0.1 pustep reduction from initial operating point as shown in Fig. 2. The similar characteristics as above are determined for exponential change in load and are illustrated in Fig. 3. From Fig. 2 and Fig. 3, the output response without controller is observed to be highly oscillatory. The open-loop Bode plot is shown in Fig. 4. The frequency response indicates low damped characteristics.

To illustrate the effectiveness, consider the above described optimal pole shift control scheme applied to heavy load operating conditions. The dominant eigenvalues are shifted to new position, (preserving the imaginary component) with desired damping coefficient $\zeta = 0.82$ so as to damp out the oscillation. Having determined the controller gain at heavy load operating point, closed-loop eigenvalues are computed from (17). Table 1 shows the closed-loop eigenvalues of the power plant under study for controller gain determined at heavy load operating point. The dominant open-loop eigenvalues and corresponding closed- loop eigenvalues are shown in boldfaced. The damping coefficient and undamped natural frequency corresponding to each open-loop eigenvalues is represented in square bracket.

Table 1. Quantitative analysis of eigenvalues with gain matrix determined with pole shift approach applied at heavy load operating point

Operating point	Open loops eigenvalues	Closed loop eigenvalues
$P_e = 1.00\,pu$ $Q_e = 0.62\,pu$ Heavy load	$-0.0408 \pm j8.948$ [0.0045/8.95] $-8.8093 \pm j9.6568$ [0.674/13.1] $-1.8389j0.7423$ [0.944/1.95] -1.8335[1.0/1.83] -2.0000[1.0/2.0] -0.7143[1.0/0.714]	$-14.4398 \pm j8.9475$ $-8.8086 \pm j9.6582$ $-15.0 \pm j0.6410$ -1.8339 -2.0000 -0.7143
$P_e = 0.80\,pu$ $Q_e = 0.25\,pu$ Normal load	$-0.0877 \pm j9.0389$ [0.0097/9.04] $-0.0877 \pm j9.0389$ $-8.8054 \pm j9.5916$ [0.67/13.0] $-1.796 \pm j0.6805$ [0.935/1.92] -1.8333[1.0/2.0] -2.000[1.0/2.0]	$-13.4258 \pm j12.96315$ -20.5732 -16.1549 $-6.5199 \pm j7.5691$ -1.8167 -1.9631 -0.7125
$P_e = 10.20\,pu$ $Q_e = 0.00\,pu$ Light load	$-0.1552 \pm j9.1137$ [0.017/9.11] $-8.8235 \pm j9.5009$ [0.681/13.0] $-1.7105 \pm j0.740$ 8[0.918/1.86] -1.8331[1.0/1.83] -2.0000[1.0/2.0] -0.7143[1.0/0.714]	-25.5578 $-13.8114 \pm j16.6734$ -16.6540 $-3.4485 \pm j7.0614$ -1.7507 -1.91453 -0.7150

Table 2. Closed loop eigenvalues obtained with computed gain matrix at normal load conditions

Normal load	Heavy load	Light load
$-14.5849 \pm j9.0374$	–	$-14.0204 \pm j16.2076$
$-8.8049 \pm j9.5930$	$18.4530 \pm j9.8151$	-24.7965
$-15.0 \pm j0.6797$	–	-16.1545
-0.7143	$7.7125 \pm j11.6110$	$-3.9679 \pm j7.002$
-2.0000	-16.7681	-0.7207
-1.8337	-7.6209	-1.9308
	-0.7150	-1.7556
	-2.0510	
	-1.8493	

The output response of power plant is shown in figures Fig.5 to Fig.9. The closed loop time response simulated with step and exponential signal at load disturbance conditions as stated above are shown in Fig. 5 and Fig. 6, respectively. The simulated response illustrates that the optimal pole shift control method brings about considerable damping effect on the output variables. As observed, the settling time and overshoot of plant output response reduced with this control approach.

The Bode plot of plant without load disturbance and with load disturbance is given Fig. 7 and Fig. 8, respectively. The response is thus non-oscillatory. The root-loci plot obtained for the plant is shown in Fig. 9. As it is observed, due to variation in nature and magnitude of disturbance, poles and zeros are located differently, which leads to significant changes in root-loci configurations.

The performance of plant response significantly gets affected due to variation in operating point. With the same gain matrix, closed-loop eigenvalues are also determined at normal and light load conditions as given in Table 1. A similar plant output response with controller is obtained for the said operating points.

To further ascertain the feasibility of this technique, optimal pole shift approach has been applied at initial operating point: $P_e = 0.8\ pu$, $Q_e = 0.25\ pu$. The controller gains are determined after shift of dominant open-loop eigenvalues to new locations. Then closed loop eigenvalues are evaluated for heavy and light load operating points and given in Table 2.

Table 3. Closed loop eigenvalues obtained with computed gain matrix at light load conditions

Normal load	Heavy load	Light load
$-15.0 \pm j9.5026$	$-24.0326 \pm j12.1913$	$-23.301 \pm j11.6621$
$-14.7450 \pm j9.1143$	$-6.7116 \pm j13.9755$	$-7.2556 \pm j13.4938$
-0.7143	$-1.0429 \pm j1.2321$	$-1.1218 \pm j1.1213$
-2.0000	-0.4464	$-3.9679 \pm j7.002$
-1.8335	-1.9082	-0.5312
$-1.7113 \pm j0.7400$	-1.2883	-1.9117
		-1.4175

In the same way, pole shift approach has been applied at operating point: $P_e = 0.2\ pu$, $Q_e = 0.0\ pu$ and subsequently closed loop eigenvalues at heavy and normal load operating points are computed. Table 3 represents the closed loop eigenvalues at the said operating point. The above study indicates that only dominant eigenvalues get shifted to new optimal locations irrespective of gain matrix determined at any operating point and subsequent changes in operating point. Thus the control gain matrix obtained using optimal pole shift approach is to a great extent independent of power plant operating points *ie* variation in operating point do not pose any threat to controller performance.

5 CONCLUSION

The hydro power plant control as SMIB system was studied in the paper. An approach towards achieving an optimal control using pole-shift satisfying a quadratic performance index was discussed. The simulation results illustrated that the optimal pole shift control method brings about considerable damping effect on the output variables. Also this method requires only a first or second order Lyapunov equation to be solved for a shift of

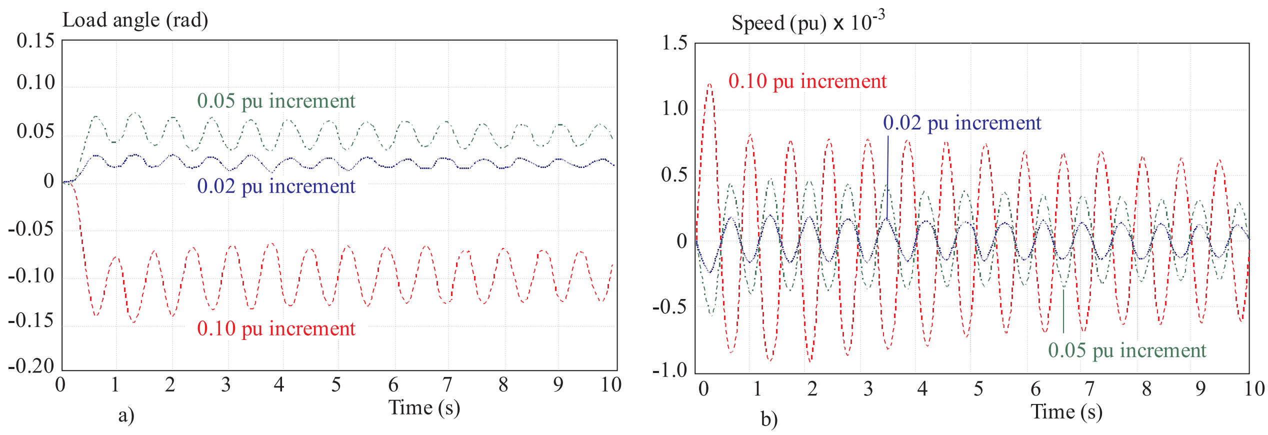

Fig. 2. Time responses of output variables for step changes in different load disturbances without controller; (a) Load angle deviation; (b) Speed deviation

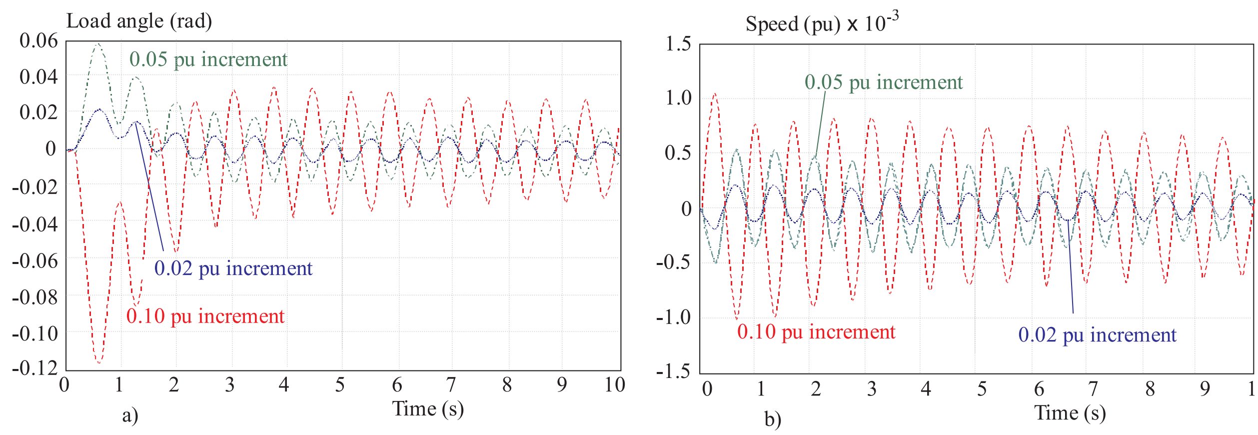

Fig. 3. Time responses of output variables for exponential changes in different load disturbances without controller; (a) Load angle deviation; (b) Speed deviation

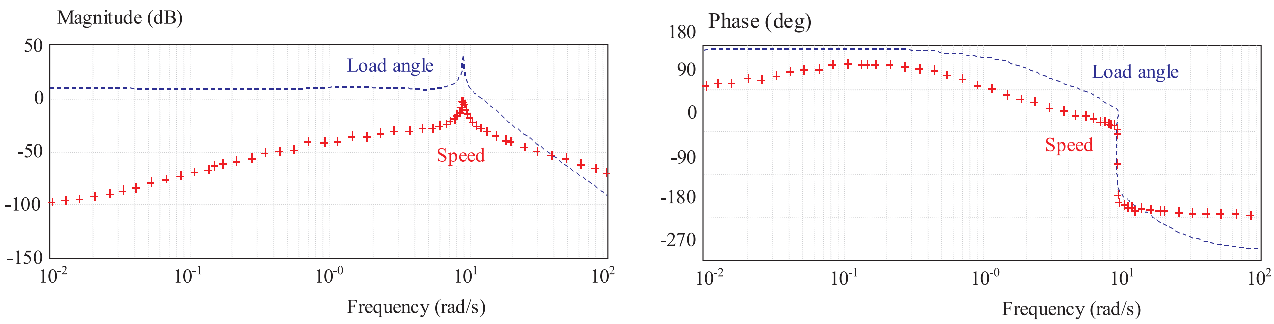

Fig. 4. Bode plot of un-compensated plant under without load disturbance

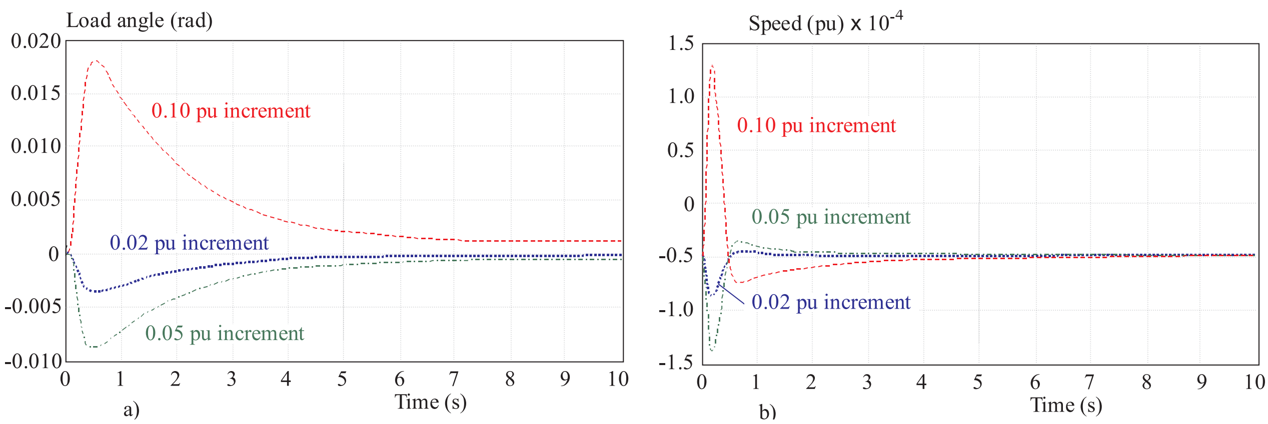

Fig. 5. Time responses of output variables for step changes in different load disturbances under the optimal pole shift based control scheme; (a) Load angle deviation; (b) Speed deviation

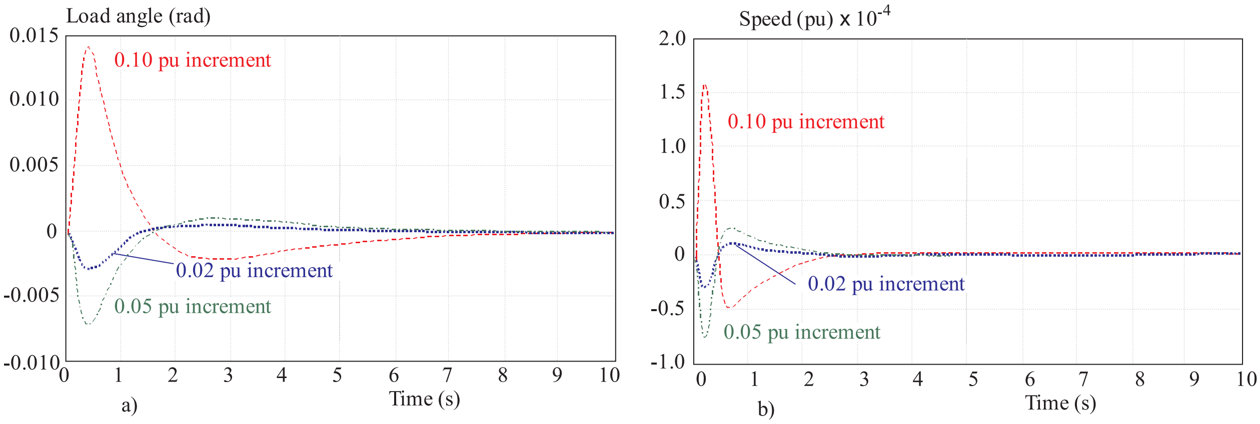

Fig. 6. Time responses of output variables for exponential changes in different load disturbances under the optimal pole shift based control scheme

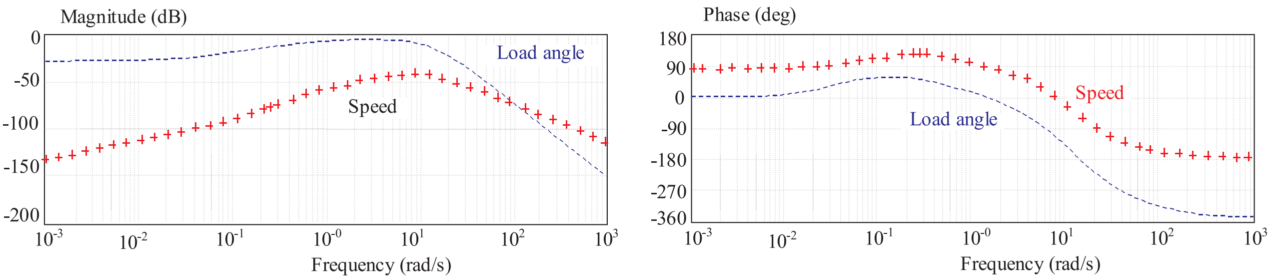

Fig. 7. Bode plot of compensated plant without load disturbance

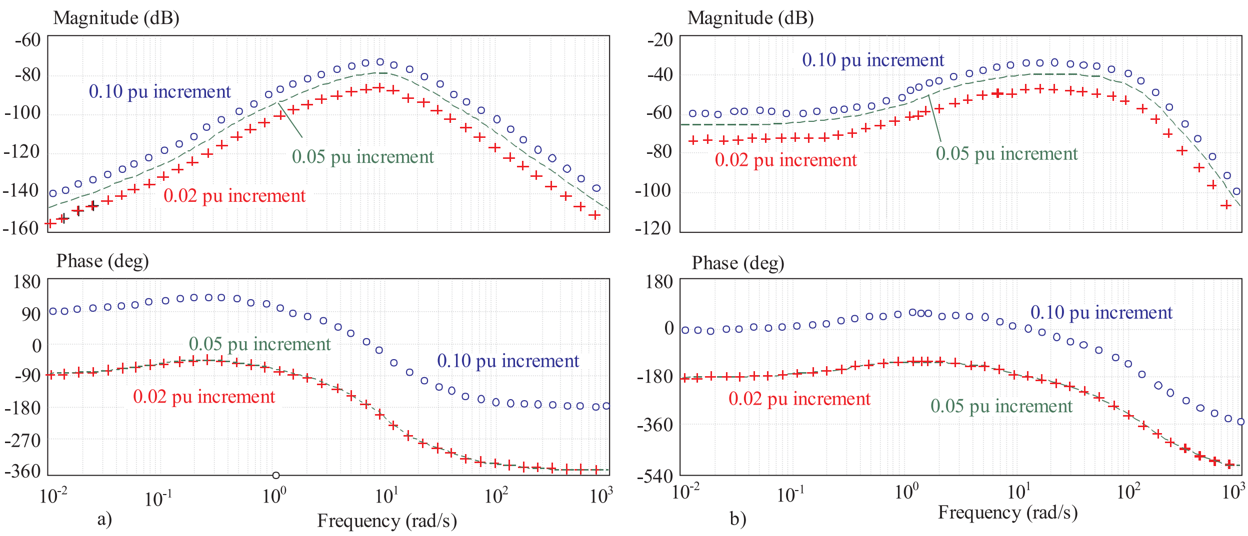

Fig. 8. Bode plot of compensated plant with load disturbance; (a) speed ; (b) load angle

real or complex pole respectively. The control gain matrix determined at any operating point leads to shift of dominant open loop eigenvalues at other operating points as well. Optimal pole shift based control scheme ensures stabilization with change in operating points.

List of Symbols

m – mechanical torque

w_0 – base angular speed (377.16 rad/sec)

w – rotor angular speed in pu

δ_l – load angle in rad

D – damping coefficient

T_a – mechanical time constant in sec

e'_q – internal transient voltage in the q-axis in pu

V_t – terminal voltage in pu

x_d – d-axis synchronous reactance in pu

x'_d – d-axis transient reactance in pu

$r_e + jx_d$ – transmission line impedance in pu

x_q – q-axis synchronous reactance in pu

K_A, K_E – voltage regulator gains

T_A, T_E – voltage regulator time constants

K_F, T_F – stabilizing transformer gain, time constant

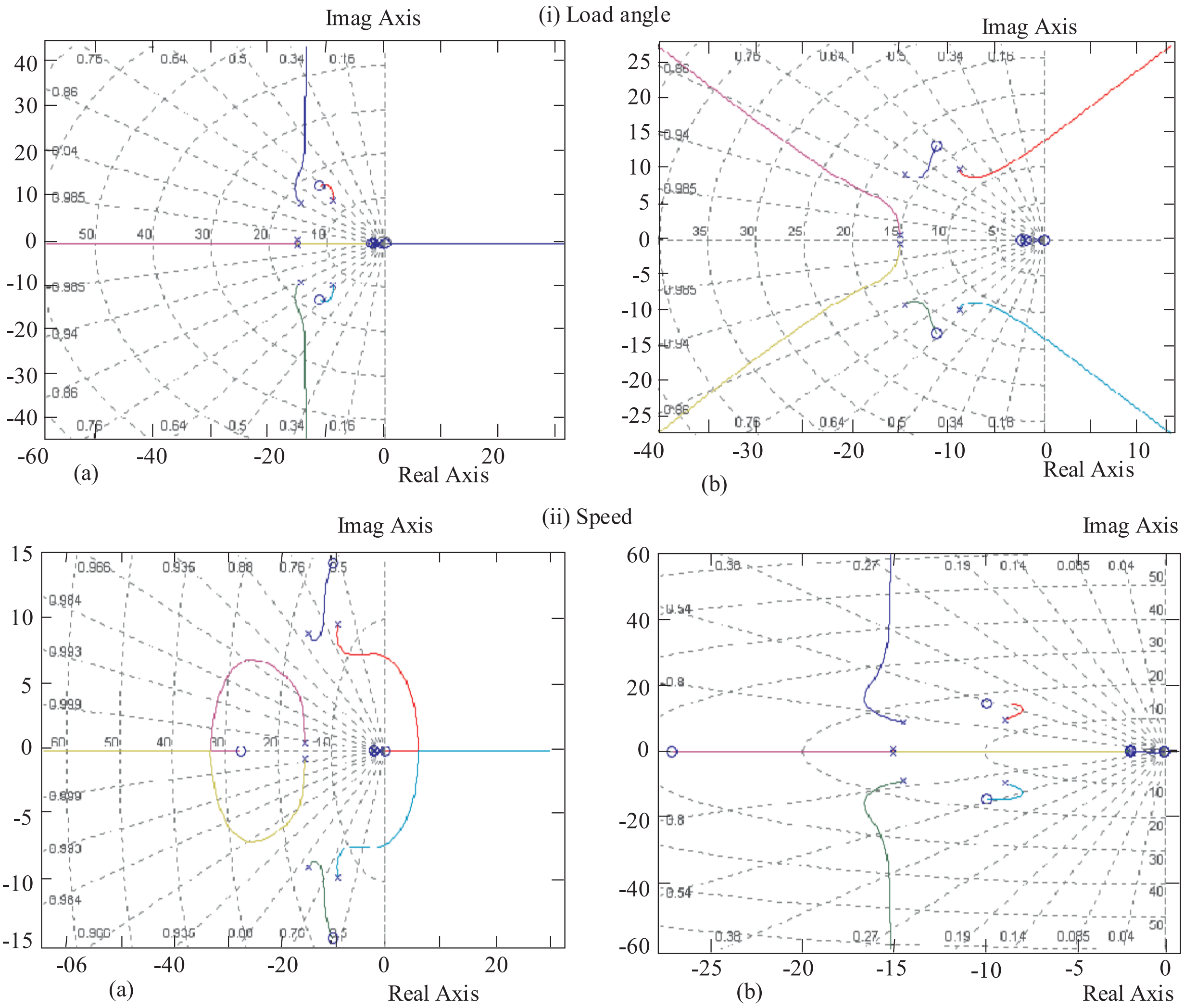

Fig. 9. Root loci of plant under various natures and magnitude of load disturbance: up (i) Load angle (a) 0.02 *pu* increment, (b) 0.1 *pu* reduction; down (ii) Speed (a) 0.02 *pu* increment, (b) 0.1 *pu* reduction

$K_1 - K_6$ – constants of the linearized model of synchronous machine
P_e, Q_e – reactive and reactive power output from synchronous machin
V_f – stabilizing transformer voltage
E_{FD} – field voltage
V_{ref} – reference voltage
V_a – regulator voltage
τ'_{d0} – d-axis open circuit field time constant

APPENDIX A [11]

$$\dot{z} = Fz + Gu \quad v = -\dot{K}z$$

with the transformation $z = C^T x$ the performance index is given as: $\dot{J} = \int\limits_0^\infty \left(z^T \dot{Q} z + v^T R v\right) \mathrm{d}t$

Shift of one real pole: Let a dominant open loop real pole $\lambda = \gamma$ is to be shifted to a new location in s-plane $s = \sigma$ for a desired damping coefficient, satisfying optimal condition: $|\sigma| > |\gamma|$. Let a positive scalar be given as: $\alpha = -(\sigma + \gamma)/2$ The first order model is given by:

$$F = \lambda \quad \text{and} \quad G = C^T B$$

In the above equation, C^T is the left eigenvector of F associated with λ. Now the solution of the first order Lyapunov equation: $(\sigma + \alpha)\dot{V} + \dot{V}(\sigma + \alpha) = \dot{H}$ with $\dot{V} = \dot{H}/(2(\sigma + \alpha))$ Thus the optimal parameters are:

$$\dot{P} = \frac{2(\sigma + \alpha)}{\dot{H}}, \quad \dot{Q} = \frac{4\alpha(\sigma + \alpha)}{\dot{H}}, \quad \dot{K} = \dot{P} R^{-1} G^T$$

Shift of complex conjugate poles:

A open loop complex conjugate pair of poles $\lambda = \gamma + j\beta$ is desired to be shifted to a new location in s-plane $s = \sigma \pm j\beta$. Let a positive scalar α be as defined above. The second order model is:

$$F = \begin{bmatrix} \gamma & \beta \\ -\beta & \gamma \end{bmatrix}, \quad G = C^T B, \quad C^T = \begin{bmatrix} c_1^T \\ c_2^T \end{bmatrix}.$$

In the above expression, $\left(c_1^T + jc_2^T\right)$ is the left eigenvector of F associated with open loop pole. Solve the second order linear Lyapuov equation

$$(F+\alpha I)\,\dot V + \dot V\left(F^T+\alpha I\right) = \dot H$$
$$\dot H = GR^{-1}G^T$$

Then optimal parameters are

$$\dot K = R^{-1}G^T\dot P, \quad \dot Q = 2\alpha \dot P, \quad \dot P = \dot V^{-1}.$$

Now for the full order model,

$$u = -Kx, \quad K = \dot K C^T$$

Then $\dot x = (A - BK)\,x$.

Shift of several poles

The resultant optimal parameters may be obtained by summation of individual ones due to shift of each poles *ie*

$$P = \sum_i P_i, \quad Q = \sum_i Q_i, \quad K = \sum_i K_i \qquad \text{(A-12)}$$

where $K_i = \dot K_i c_i^T, \quad P_i = c_i \dot P_i c_i^T, \quad Q_i = 2\alpha_i P_i.$

APPENDIX B

The plant data are as follows:

$$\begin{array}{ccc}
S_n = 131\,\text{MVA}, & V_n = 13.8\,\text{kV}, & x''_d = 0.330 \\
x'_d = 0.360, & x_d = 1.010, & x''_q = 0.330 \\
x'_q = 0.57, & x_q = 0.57, & r_a = 0.00 \\
\tau''_d = 0.030\text{s}, & \tau' d = 2.7\text{s}, & \tau''_{d0} = 0.030\text{s} \\
\tau'_{d0} = 7.6\text{s}, & D = 0.0, & K_E = -0.17 \\
T_A = 0.05, & T_E = 0.95, & K_A = 400 \\
K_F = 0.025, & T_F = 1.0, & T_w = 2.23\text{s}
\end{array}$$

Acknowledgment

The authors would like to acknowledge the assistance received from Dr. A. M. Yousuf, Department of Electrical Engineering, Assiut University, Assuit, Egypt for fruitful discussion on the results obtained in the application of optimal pole shift for hydropower plant control.

References

[1] DJUKANOVIC, M.;—NOVICEVIC, M.—DOBRIJEVIC, Dj.—BABIC, B.—SOBAJIC, D. J.— PAO, Y. H.: Neural-net based coordinated stabilizing control for the exciter and governor loops of low-head hydropower plants, IEEE Trans. Energy Conversion **10** No. 4 (1995), 760–767.

[2] GHANDAKLY, A. A.—DAI, J. J.: An adaptive synchronous generator stabilizer design by generalized multivariable pole shifting (GMPS) technique, IEEE Trans. on Power Systems **7** No. 3 (1992), 1239–1244.

[3] MALIK, O. P.—CHEN, G. P.—HOPE, G. S.—QIN, Y. H.—XU, G. Y.: Adaptive self-optimizing pole shifting control algorithm, IEE Proceedings-D **139** No. 5 (1992), 429–438.

[4] MALIK, O. P.—CHEN, G. P.—HOPE, G. S.—QIN, Y. H.—XU, G. Y.: An adaptive power system stabilizer based on the self-optimizing pole shifting control strategy, IEEE Trans. on Energy Conversion **8** No. 4 (1993), 639–645.

[5] KOTHARI, M. L.—BHATTACHARYA, K.—NANDA, J.: Adaptive power system stabilizer based on pole-shifting technique, IEE Proc.-Gener. Transm. Distrib. **143** No. 1 (1996), 96–98.

[6] RAMAKRISHNA, G.—MALIK, O. P.: RBF identifier and pole shifting controller for PSS application, Proc. of International Conference on Electric Machines and Drives IEMD' 99 (May 1999), 589–591.

[7] ABDELAZIM, T.—MALIK, O. P.: Fuzzy logic based identifier and pole-shifting controller for PSS application, Proc. of IEEE Power Engg. Society General Meeting (July 2003), 1680–1685.

[8] ZENG, Y.—MALIK, O. P.: Robust adaptive controller design based on pole-shifting technique, Proc. of the 32nd Conference on Decision and Control (1993), 2353–2357.

[9] GEl-SHERBINY, M. K.—HASAN, M. M.—El-SAADY, G.—YOUSEF, A. M.: Optimal pole shifting for power system stabilization., Electric Power Syst. Research No. 66 (2003), 253–258.

[10] KISHOR, N.—SAINI, R. P.—SINGH, S. P.: Coordinated control for the exciter and governor in a small hydropower plant, Proc. of National Power System Conference, Indian Institute of Technology, Madras, Dec. 27–30, 2004, 431–436.

[11] AMIN, M. H.: Optimal pole shifting for continuous multivariable linear systems, Int. Journal of Control **41** No. 3 (1985), 701–707.

[12] HERRON, J—WOZNIAK, L. M.: A State-space pressure and speed sensing governor for hydrogenerators, IEEE Trans. on Energy Conversion **6** No. 3 (1991), 414–418.

[13] ARNAUTOVIC, D. B.—SKATARIC, D. M.: Sub-optimal design of hydro-turbine governors, IEEE Trans. on Energy Conversion **6** No. 3 (1991), 438–444.

[14] ABDEL-MAGID, Y. L.—BETTAYEB, M.—SELIM, SZ.: Power system output feedback stabilizer design via genetic algorithms, Proc. of Genetic Algorithms in Engineering Systems – Innovation and Applications, Sept. 2-4, 1997, 56–62.

Received 5 July 2005

Nand Kishor received BE in Electrical Engineering and M Tech in Energy Management in 1996 and 1999 respectively. Currently he is in his final year of PhD degree course at Indian Institute of Technology, Roorkee, India. He is a student member of IEEE.

R. P. Saini obtained BE in Mechanical Engineering from University of Mysore, India in 1982, ME and PhD from University of Roorkee in 1989 and 1996 respectively. Presently he is serving as Senior Scientific Officer in Indian Institute of Technology, Roorkee. He is a life member of International Association for Small Hydro, Indian Society for Continuing Engineering Education and Solar Energy Society of India. His interest includes small hydro power development, renewable energy technologies and solar PV system, design and applications.

S. P. Singh received BSc in Electrical Engineering from Aligarh Muslim University, Aligarh in 1978, ME in 1980 and PhD in 1993 from University of Roorkee, India. He is serving as Associate Professor at Indian Institute of Technology, Roorkee. His area of research includes power plant operation and control, electrical machine analysis, self and line excited induction generators.