Damping of Power System Oscillations by Using Coordinated Control of PSS and STATCOM Devices

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Abstract

The main objective of this paper is to investigate the power system stability enhancement via coordinated control of PSS and static synchronous compensator (STATCOM) based controllers. Also, investigate the effectiveness and dynamic interaction of STATCOM controllers in damping system oscillation. Proposed optimal pole shifting technique to design damping controller of excitation system (PSS) and STATCOM based controller. The method is based on modern control theory for multi-input and multi-output system. Several control schemes are proposed. The effectiveness of the proposed control schemes in improving the power system is verified through eigenvalues and time domain simulations under nominal loading conditions. The analysis of cases under study show that, the STATCOM – based controller has good effect on improving system damping and the coordinated control of PSS and STATCOM– based controller provide the best means for stabilizing power system, more damping with less control effort than individual control.
Keywords: coordination , optimal control, FACTS, STATCOM

اخماد تذبذبات منظومة القدرة بتنسيق السيطرة PSS وجهاز STATCOM

الخلاصة

يهدف هذا البحث الى تعزيز استقرارية منظومة القدرة بالسيطرة المتناسقة بين موازن القدرة (PSS) ومسيطرات جهاز (STATCOM) وايضا تم دراسة تاثير التفاعل الديناميكي لمسيطرات ال STATCOM في اخماد تذبذبات منظومة القدرة. اقترحت طريقة (Optimal Pole Shifting) لتصميم مسيطرات اخماد لمنظومة الاثارة ومسيطرات ال STATCOM . تم اقتراح عدة مخططات سيطرة. ان تأثير مخططات السيطرة المقترحة بهدف تحسين ديناميكية منظومة القدرة قد اثبتت من خلال تحليل جذور المعادلة المميزة (Eigenvalue) والمحاكاة الزمنية تحت ظروف تحميل مختلفة. ان تحليل الحالات تحت البحث يظهر ان تاثير المسيطر المسند STATCOM الافضل في تحسين توهين المنظومة والسيطرة المنسقة لمسيطر PSS and STATCOM توفر افضل الطرق لاستقرارية نظام القدرة اي توهين اكبر بجهد سيطرة اقل من السيطرة المنفردة .

Introduction

The most important concept of power system stability control is the energy balance between mechanical input power to a generator and its output power at all times [1]. Today's, electric power demand has grown rapidly , therefore , the need for more complex power systems has arisen, on the other hand , expansion in transmission and generation is restricted with the limited

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availability of resources and the strict environmental constraints. Therefore, power utilities are forced to rely on utilization of existing generating units and to load existing transmission lines close to their thermal limits. However, stability has to be maintained at all times. Hence, in order to operate power systems effectively, without reduction in system security and quality of supply, even in the case of contingency conditions such as, loss of transmission lines and /or generating units , new control strategies need to be implemented .

The advances in the field of power electronics led to a new approach introduced by the Electric Power Research Institute (EPRI) called flexible AC transmission system or simply FACTS , which came as an answer to a call for more efficient use of already existing resources in present power systems, while maintaining and even improving power system security[2-4].

The interconnection between distant located power systems is now a common practice, which gives rise to low frequency oscillations in the range of 0.1– 3 Hz. If not well damped, these oscillations may keep growing in magnitude until loss of synchronism results [5].

In order to damp these power system oscillations and increase system stability, the installation of power system stabilizer (PSS) is both economical and effective. PSSs have been used for many years to add damping to electromechanical oscillation. To date, most major electric power system plants in many countries are equipped with PSS. However, PSSs suffer a drawback of being liable to cause great variations in the voltage profile and may not be able to suppress oscillations resulting from severe disturbances, especially those three – phase faults, which may occur at the generator terminals[6].

Recently, FACTS – based stabilizer has appeared offering an alternative way in damping power system oscillation. Although , the damping ratio of FACTS controllers often is not their primary function , the capability of FACTS – based stabilizers to increase power system oscillation damping characteristics has been recognized [7]. However, possible interaction between PSSs and FACTS – based stabilizers, may deteriorate much of their contributions, and may even cause adverse effect on damping of system oscillations. Therefore, coordinated design of PSSs and FACTS – based stabilizers is a necessity, both to make use of the advantages of the different stabilizers and to avoid the demerits accompanied with their operation. The static synchronous compensator (STATCOM) is one of the important FACTS devices and can be used for dynamic compensation of power system to provide voltage support and stability improvement. This work , investigate the effectiveness of the coordinated design of power system stabilizers (PSS) and STATCOM-based controllers to improve power system dynamic stability.

Power System Model

The power system is represented by single machine infinite bus power system (SMIB) installed with a STSTCOM at the midpoint of the line through a step-down transformer as shown in fig. 1.

Generator Model

The generator is represented by third-order model comprising of the electromechanical swing equation and the generator internal voltage equation [8].

$$\frac{dd}{dt} = w_b\left(w - 1\right) \qquad \ldots (1)$$

$$\frac{dw}{dt} = \frac{1}{M}\left(p_m - p_e - D\left(w - 1\right)\right)$$

... (2)

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}\left(E_{fd} - (x_d - x'_d)i_d - E'_q\right) \quad ...(3)$$

$$p_e = v_d i_d + v_q i_q \quad ...(4)$$

$$v_d = x_q i_q \quad ...(5)$$

$$v_q = E'_q - x'_d i_d \quad ...(6)$$

2.2 Excitation System Model

The excitation system is represented by a first order model (IEEE type– STI system), shown in fig. (2) [9].

The equation describing it can be written as:

$$\frac{dE_{fd}}{dt} = \frac{1}{T_a}\left[K_a\left(v_{ref} - v + U_{pss}\right) - E_{fd}\right] \quad ...(7)$$

STATCOM Model

The STATCOM is modeled as a voltage–sourced converter behind a step down transformer as shown in fig.1. There are two basic controllers implemented in STATCOM, a DC and AC voltage regulation shown in figs. (3) and (4) respectively.

The STATCOM generates a controllable AC voltage given by [10].

$$\bar{v}_S = cv_{DC}\angle y = cv_{DC}(\cos y + j\sin y)$$

For PWM inverter c=mk, where m is the modulation ratio defined by Pulse Width Modulation (PWM), k is the ratio between AC and DC voltage depending on the converter structure. v_{DC} is the DC voltage, and y is the phase defined by PWM. The magnitude and phase of $\bar{v}_S$ can be controlled through C and y respectively. By adjusting the STATCOM AC voltage $\bar{v}_S$, the active and reactive power exchange between the STATCOM and power system can be controlled . Capacitor voltage dynamics has big influences on power system, so capacitor voltage dynamic should be considered. If converter is assumed to be lossless, the exchanged active power between converter and system is equal to the active power that exchanges between capacitor and converter $(P_{DC} = P_{AC})$. So with these assumptions, the relationship between voltage and current of capacitor, can be expressed as:

$$v_{DC}i_{DC} = real\left(\bar{v}_s i_s^*\right) = real\left[cv_{DC}(\cos y + j\sin y)(i_{sd} - ji_{sq})\right] \quad ...(8)$$

Solving the above equation for i_{DC} gives:

$$i_{DC} = c\left(i_{sd}\cos y + i_{sq}\sin y\right) \quad ...(9)$$

$$\dot{v}_{DC} = \frac{c}{C_{DC}}\left(i_{sd}\cos y + i_{sq}\sin y\right) \quad ..(10)$$

where v_{DC} and i_{DC} are the capacitor voltage and current respectively, and i_{sd}, i_{sq} are the d and q axis of STATCOM current.

linearized Model

In the design of power oscillation damping controller the linearized incremental model around a nominal operation point is usually employed. Linearized the system model yield the following state equation

$$\dot{x} = Ax(t) + Bu(t) \quad ...(11)$$

where x represents the nine state variables of the system under study. The state variables are $\Delta\delta, \Delta\omega \; and \; \Delta E'_q$ for the generator, ΔE_{fd} for exciter system, and $\Delta V_{DC}, \Delta x_1, \Delta \Psi, \Delta x_4, and\ \Delta C$ for the STATCOM and their AC/DC voltage regulators. Equation (11) may then be re-written in matrix form as:

$$A=\begin{bmatrix} 0 & w_b & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-k_1}{M} & \frac{-D}{M} & \frac{-k_2}{M} & 0 & \frac{-k_{PDC}}{M} & 0 & \frac{-k_{P\Psi}}{M} & 0 & \frac{-k_{PC}}{M} \\ \frac{-k_4}{T'_{do}} & 0 & \frac{-k_3}{T'_{do}} & \frac{1}{T'_{do}} & \frac{-k_{qDC}}{T'_{do}} & 0 & \frac{-k_{q\Psi}}{T'_{do}} & 0 & \frac{-k_{qc}}{T'_{do}} \\ \frac{k_A k_5}{T_A} & 0 & \frac{k_A k_6}{T_A} & \frac{-1}{T_A} & \frac{k_A k_{VDC}}{T_A} & 0 & \frac{k_A k_{v\Psi}}{T_A} & 0 & \frac{k_A k_{vc}}{T_A} \\ k_7 & 0 & k_8 & 0 & k_9 & 0 & k_{D\Psi} & 0 & k_{DC} \\ 0 & 0 & 0 & 0 & -k_{IDC} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-k_{PDC} k_s}{T_s} & \frac{k_s}{T_s} & \frac{-1}{T_s} & 0 & 0 \\ -k_{IAC} f_{21} & 0 & -k_{IAC} f_{22} & 0 & -k_{IAC} f_{25} & 0 & -k_{IAC} f_{23} & 0 & -k_{IAC} f_{24} \\ \frac{-k_F k_{PAC} f_{21}}{T_F} & 0 & \frac{-k_F k_{PAC} f_{22}}{T_F} & 0 & \frac{-k_F k_{PAC} f_{25}}{T_F} & 0 & \frac{-k_F k_{PAC} f_{23}}{T_F} & \frac{k_F}{T_F} & -\left(\frac{1}{T_F} + \frac{k_F k_A f_{24}}{T_F}\right) \end{bmatrix}$$

$$B=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{k_A}{T_A} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & k_{IDC} & 0 \\ 0 & \frac{k_{PDC}\, k_s}{T_s} & 0 \\ 0 & 0 & k_{IAC} \\ 0 & 0 & \frac{k_f\, k_{PAC}}{T_F} \end{bmatrix}$$

The derivation details of equation (11) are given in [11].

<u>Optimal Pole Shifting Technique</u>

Consider the completely controllable linear time – invariant multivariable system, equation (11)

where the dimensions of the state vector x and the control vector U are (nx1) and (mx1) respectively, and A and B are constant matrices of appropriate dimensions. Let the n-poles of the open-loop system (11) be denoted by (λ_{oi}). If a feedback control law

$$U(t) = -Kx(t) \qquad \dots (12)$$

is applied to equation (*11*), a closed loop system will be obtained in the form

$$\dot{x} = A_c x(t) \text{ with } A_c = A - BK \dots (13)$$

Consider $\lambda_{ci} = \mathrm{Re}(\lambda_{ci}) + j\,\mathrm{Im}(\lambda_{ci})$, being a closed loop pole of equation (*13*). If system matrix A is a non– singular matrix, then for the following algebraic equation

$$PA + A^T P - PBB^T P = 0 \qquad \dots (14)$$

there exists a positive semi – definite symmetric solution P satisfying [12].

Re (λ_{ci}) < 0 and

$\lambda_{ci}^2 = \lambda_{oi}^2$ with i = 1, 2, … , n

where (λ_{oi}) and (λ_{ci}) are the open and closed loop poles with the feedback $K = B^T P$.

Using the above property, then, for the following matrix algebraic equation

$$P(A + gI) + (A^T + gI)P - PBR^{-1}B^T P = 0 \qquad \dots (15)$$

where γ is a positive real constant scalar and **R** a positive definite symmetric matrix. There exists positive semi-definite real symmetric solution P satisfying

Re(λ_{ci}) ≤ – γ and

$$(\lambda_{ci} + g)^2 = (\lambda_{oi} + g)^2 \qquad \dots (16\text{-a})$$

with i = 1, 2, … , n and

$$K = R^{-1} B^T P \qquad \dots (16\text{-b})$$

Furthermore, the feedback control law $U = -Kx$ minimizes the following quadratic performance index

$$J = \int_0^\infty (x^T Q x + U^T R U) dt \quad \text{with} \quad Q = 2gP \qquad \ldots (17)$$

Condition (16-a) follows directly from the mirror – image property. Relation (17) is obvious from (*15*) and the Riccati equation.

The linear matrix Lyapunov equation is given by

$$(A + gI)V + V(A^T + gI) = H \ldots \quad (18)$$

with $H = BR^{-1}B^T$

The conditions of the controllability of the pair (A, B) together with the positive definitions of **R** imply that the pair $((-A - gI), BR^{-1/2})$ is controllable [13]

Now, rewriting equation (18) in the form

$$(-A - gI)V + V(-A^T - gI) = -DD^T$$

with $D = BR^{-1/2}$ … (19)

It follows that the existence of the unique positive definite solution V of equation (*18*) is guaranteed as stated by Lyapunov Iemma [13]. Applying the feedback matrix $K = R^{-1}B^T P$ to equation (11).

$$A_c = A - HP \quad \text{with} \quad H = BR^{-1}B^T \qquad \ldots (20)$$

Post multiplying equation (18) by P, one obtains

$$(A + gI) + V(A^T + gI)P = HP \qquad \ldots (21)$$

Then, substituting equation (21) into equation (20) yields

$$A_c = -(P^{-1}A^T P + 2gI)$$

$$\text{Re}(l_{ci}) = -(2g + \text{Re}(l_{oi})) \qquad \ldots (22)$$

Problem Statement

For the controllable system described by equation (11), it is required to design a feedback matrix K, which shifts the real part of the open loop system poles **(**λ_{oi}**)** to the n desired positions $(s_i = \text{Re}(l_{ci}))$ .At the same time, K would minimize a standard quadratic performance index with a preassigned control weighting matrix R. The performance index is described by

$$J = \int_0^\infty (x^T Q x + U^T R U) dt$$

Design Procedure

For shifting one pole or a complex pair of poles, let a reduced order model of the system (11) be represented by [14].

$$\dot{Z}(t) = FZ(t) + GU(t),$$

$$U(t) = -\dot{K}\, Z(t) \qquad \ldots (23)$$

where

$$Z(t) = C_t x(t) \qquad \ldots (24)$$

C_t is the aggregation matrix of order (r*n). The matrices F and G are given by

$$C_t A = FC_t \qquad \ldots (25\text{-a})$$

$$G = C_t B \qquad \dots (25\text{-b})$$

By a suitable choice of the constant matrix C_t , it is possible to ensure the eigenvalues of A. Let matrix C_t be chosen as

$$C_t = TM^{-1} \qquad \dots (26)$$

where

T = [I_r 0]

I_r = r*r identity matrix

M = model matrix of A

The first r columns of M are the eigenvectors corresponding to the r eigenvalues of A that needs to be reassigned. The above choice of C_t ensures that the eigenvalues of **F** are identical to these r eigenvalues of **A** that need to be reallocated, and the standard performance index

$$\dot{J} = \int_0^\infty (Z^T \dot{Q} Z + U^T R U) dt \quad \dots (27)$$

is to be considered for each of the following cases.

Case I (Shifting one real pole)

A real pole $\boldsymbol{\lambda_{oi}} = \boldsymbol{\sigma_{oi}}$ is to be shifted to the new position $\boldsymbol{\lambda_c} = \boldsymbol{\sigma}$. The first order model to be used is defined by equation (23) and (25) with

F = $\boldsymbol{\lambda_o}$ and **G** = $\mathbf{C_t B}$

where C_t is the left eigenvector of A associated with λ_o. If the positive scalar α is chosen as

$$g = -\left(\frac{s + s_{oi}}{\mathbf{2}}\right)$$

The solution of the first order Lyapunov equation

$$(s + g)\dot{V} + \dot{V}(s + g) = \dot{H} \qquad \dots (28)$$

is given by

$$\dot{V} = \frac{\dot{H}}{2(s + g)} \qquad \dots (29)$$

Then the required parameters are found to be

$$\dot{P} = \dot{V}^{-1} = \frac{2(s + g)}{\dot{H}} \quad \dots (30)$$

Substituting equation (30) into equations (17) and (16) gives.

$$\dot{Q} = \frac{4g(s + g)}{\dot{H}} \quad \dots (31\text{-a})$$

$$\dot{K} = \mathbf{[2(}s + g\mathbf{)} / \dot{H}\mathbf{]} R^{-1} B^T \quad \dots (31\text{-b})$$

Case II (Shifting a complex conjugate pair of poles)

A complex conjugate pair of poles $l_o = s_{oi} \pm jb$, are to be shifted to the new position $l_c = s + jb$. Let the position scalar γ be chosen as

$$g = -\frac{(s + s_{oi})}{2}$$

The second-order model to be used is defined by equations (23) and (25) with

$$F=\begin{bmatrix} s_{oi} & b \\ -b & s_{oi} \end{bmatrix}, \qquad G=C_t^T B$$

and $$C_t^T=\begin{bmatrix} C_{t1}^T \\ C_{t2}^T \end{bmatrix}$$

where **(C_{t1}, C_{t2})** are the left eigenvector of A associated with pole $l_o = g \pm jb$. By solving the following second order linear Lyapuonov equation

$$(F+gI)\dot{V}+\dot{V}(F^T+gI)=\dot{H},$$

$$\dot{H}=GR^{-1}G^T \qquad \ldots (32)$$

The parameters of the corresponding second order optimal problem are obtained from

$$\dot{P}=\dot{V}^{-1}, \quad \dot{Q}=2g\,\dot{P} \quad \text{and}$$

$$\dot{K}=R^{-1}G^T\dot{P} \qquad \ldots (33)$$

The relations between these parameters and those of the full order problem defined by (11) can be found, as follows: Substituting equation (24) into (23) yields

$$U(t)=-Kx(t) \quad \text{with}$$

$$K=\dot{K}C_t^T \qquad \ldots (34)$$

If this control law is applied to the full-order open loop system, then the full-order closed loop system is given by

$$\dot{x}=(A-BK)x \qquad \ldots (35\text{-a})$$

$$K=\dot{K}C_t^T=R^{-1}G^T\dot{P}C_t^T \quad \ldots (35\text{-b})$$

The n-poles of (35-a) are those of (F – G$\dot{K}$) in addition to the undisturbed open–loop poles of equation (11). Therefore, the required pole shifting can be achieved by using the feed-back control law, equation (34). Its optimality can be proved by premultiplying and postmultiplying equation (32) by $C_t\,\dot{P}$ and $\dot{P}\,C_t^T$ which yields

It follows from equations (32) and (34) and the above equation that

$$PA+A^TP-PBR^{-1}B^TP+Q=0$$

and $$K=\dot{K}C_t^T=R^{-1}B^TP$$

with $P=C_t\,\dot{P}\,C_t^T$ and $Q=2gP$

The problem of shifting several poles may be solved by the recursive applications of the reduced– order optimal shifting problem. The resulting feedback matrices (**K_i**) and the resulting matrices **Q** and **P** can be constructed by the summation of the matrices **Q_i** and **P_i** respectively. i. e.

$$P=\sum_i P_i, \quad Q=\sum_i Q_i \quad \text{and}$$

$$K=\sum_i K_i$$

where $K_i = \dot{K}_i C_{ti}^T$,

$$P_i = C_{ti}\dot{P}_i C_{ti}^T$$

and $Q_i = 2g_i P_i$

with $$g_i=\frac{-\mathrm{Re}(l_{ci}+l_{oi})}{2}$$

Design OPS Damping Controller for SMIB Equipped with STATCOM

The ability of proposed optimal power system stabilizer and optimal STATCOM based controller to dampen out the power system oscillation are investigated. Also the effectiveness of coordinated design of power system stabilizers and STATCOM – based stabilizers to improve power system dynamic

$$C_t \dot{P} F C_t^T + C_t F \dot{P} C_t^T - C_t \dot{P} G R^{-1} G^T \dot{P} C_t^T + C_t \dot{Q} C_t^T = 0$$

stability are investigated. several control schemes are proposed .

Schemes (1) : where PSS only is considered

Schemes (2) : where only STATCOM controller is considered .

Schemes (3) : where coordinated design of both PSS and STATCOM controller is considered .

Simulation and Results

The K – constants of the model are computed for nominal operating condition and system parameters (the system data are given in Appendix), and are given below:

$K_1 = 0.3564 \qquad K_2 = 0.8254$

$K_3 = 1.6 \qquad K_4 = 0.1218$

$K_5 = 0.0145 \qquad K_6 = 0.6828$

$K_7 = -0.4196 \qquad K_8 = 0.498$

$K_9 = 0.052 \qquad K_{pDC} = 0.1029$

$K_{pc} = 0.4114 \qquad K_{p\psi} = -0.1774$

$K_{qc} = -0.315 \qquad K_{qDC} = -0.0788$

$K_{q\psi} = -0.061 \qquad K_{vDC} = 0.0553$

$K_{vc} = 0.2212 \qquad K_{v\psi} = -0.0068$

$K_{DC} = -0.1539 \qquad K_{d\psi} = 1.4075$

Substituting these values into the state space equation (11), the numerical values of the system matrix A, is calculated and is given as

$$A = \begin{bmatrix} 0 & 377 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.059 & -0.667 & -0.1376 & 0 & -0.017 & 0 & 0.0296 & 0 & -1.6458 \\ -0.024 & 0 & -0.3172 & 0.1983 & 0.0156 & 0 & 0.0122 & 0 & 0.0625 \\ -14.501 & 0 & -682.79 & -20 & -55.293 & 0 & 6.789 & 0 & 221.173 \\ -0.4196 & 0 & 0.4984 & 0 & -0.052 & 0 & 1.4075 & 0 & -0.153 \\ 0 & 0 & 0 & 0 & -0.2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -10 & 20 & -20 & 0 & 0 \\ 0.0097 & 0 & 0.0227 & 0 & 0.0195 & 0 & 0.0118 & 0 & 0.0782 \\ 0.4831 & 0 & 1.133 & 0 & 0.9772 & 0 & 0.589 & 20 & -18.867 \end{bmatrix}$$

The dynamic behavior of the system is recognized through the eigenstructure of the system matrix A, hence solving the system characteristic equation $|\lambda I - A|$, the eigenstructures of the system are computed and given as:

$\lambda_1 = -0.123 + j5.96$

$\lambda_2 = -0.123 - j5.96$

$\lambda_3 = -0.171 + j0.46$

$\lambda_4 = -0.171 - j0.46$

$\lambda_5 = -0.24$

$\lambda_6 = -10.2 + j5.8$

$\lambda_7 = -10.2 - j5.8$

$\lambda_8 = -18.8$

$\lambda_9 = -19.7$

It is clear from the eigenstructure, the system is oscillatory and would take a long time to reach the steady state due to the presence of dominant complex eigenvalues $(\lambda_1, \lambda_2, \lambda_3 \ and \ \lambda_4)$ close to the imaginary axis.

The behavior of the system can be easily understood by solving the state equation. Equation (11) is solved numerically, using Ranga – Kutta method. The open loop responses of state variables (load angle and speed deviation) to 10% step change in mechanical power input are shown in figures (5) and (6). The system is stable but with high amount of oscillations, it would take a long time to reach the steady state. Hence, then stability of the system must be improved. Thus, several control schemes are proposed as follows:

Scheme (1):

To damp the unwanted oscillations in the system, OPS is applied to the design of optimal power system stabilizer (PSS). The four dominant eigenvalues $(\lambda_1, \lambda_2, \lambda_3 \ and \ \lambda_4)$ are shifted to new location in stable region on complex plane. The criteria for choosing the new position are the nearest negative real part to the original eigenvalue that ensure stability. There are some constraints taken into account, such as the accepted time domain characteristic (time constant and damping ratio). According to these constraints, four new locations for dominant modes are proposed, they are:

$\lambda_1 = -4 + j5.96$

$\lambda_2 = -4 - j5.96$

$\lambda_3 = -1.5 + j0.4589$

$\lambda_4 = -1.5 - j0.4589$

The input matrix B is given as:

$B = [0 \quad 0 \quad 0 \quad {}^{k_A}/_{T_A} \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$

And

$U = [U_{PSS}]$ and

$R = [1]$

The OPS controller is introduced into the system, and the gain for each state variable is computed and given in table (1)

To verify the validity of the proposed design algorithm, the eigenstructure of the closed loop (modified) system is figured out. The closed loop eigenstructures are:

$$\lambda_1 = -4 + j5.96$$
$$\lambda_2 = -4 - j5.96$$
$$\lambda_3 = -1.5 + j0.46$$
$$\lambda_4 = -1.5 - j0.46$$
$$\lambda_5 = -0.24$$
$$\lambda_6 = -10.2 + j5.8$$
$$\lambda_7 = -10.2 - j5.8$$
$$\lambda_8 = -18.8$$
$$\lambda_9 = -19.7$$

It is observed from eigenstructure, only the dominant eigenvalues are shifted and the other eigenvalues remained unchanged. This reveals the fact that the proposed controller improves system damping surely.

Scheme (2):

The optimal pole shifting algorithm is applied to design optimal ψ-based controller. The state space equation of this case is the same as that of scheme (1) except the input matrix B is given as:

$B = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad k_{IDC} \quad k_s k_{PDC}/T_s \quad 0 \quad 0]$

$U = [U_\psi]$ and $R = [1]$

The OPS algorithm is used to shift the dominant eigenvalues ($\lambda_1, \lambda_2, \lambda_3$ *and* λ_4) to new location, and all the state variable are fed back to the system input (U_ψ) through weight factor for each state. The new locations for dominant eigenvalues are proposed in scheme (1). The OPS ψ-based controller is introduced into the system, and the gain for each state variable is computed, and given in table (2)

Scheme (3):

The OPS algorithm is applied to design optimal C-based controller. The state space equation of this case is the same as that of scheme (1) except the input matrix B is given as:

$B = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad k_{IAC} \quad k_F k_{PAC}/T_F]$

$U = [U_C]$ and $R = [1]$

The OPS algorithm is used to shift the dominant eigenvalues ($\lambda_1, \lambda_2, \lambda_3$ *and* λ_4) to new location, all the state variables are fed back to the system input (U_C) through weight factor for each state. The new locations for dominant eigenvalues are proposed in scheme (1). The OPS C-based controller is introduced into the system, and the gain for each state variable is computed, and given in table (3).

To support the result of the eigenvalue analysis, the performance of the system with proposed scheme controllers, (scheme1, scheme2, and scheme 3), are tested with 10% step change in mechanical power input. Figures (7) and (8) show the load angle and speed deviation response with proposed PSS, ψ, and C-based controller all at one figure for better clarification. It can be seen that the STATCOM ψ-based controller and PSS provide an excellent damping characteristic and enhance the stability, while the system damping is slightly improved in case of C-based controller.

Scheme (4):

From the time domain simulation of the previous schemes, it is observed that, the C-based controller does not perform well and has poor capabilities in damping the system oscillation.

In this case, the OPS algorithm is applied to the designed optimal controller that coordinates power system stabilizer (PSS) and STATCOM C – based controller. The state space equation of this case is the same as that of scheme (1) except the input matrix B is given as:

$$B = \begin{bmatrix} 0 & 0 & 0 & k_A/T_A & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & k_{IAC} & k_F k_{PAC}/T_F \end{bmatrix}$$

And

$$U = \begin{bmatrix} U_{PSS} \\ U_C \end{bmatrix} \quad \text{and} \quad R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The OPS algorithm is used to shift the dominant eigenvalues $(\lambda_1, \lambda_2, \lambda_3 \text{ and } \lambda_4)$ to new location, all the state variable are fed back to the system inputs $(U_{PSS} \text{ and } U_C)$ through weight factor for each state.

The new locations for dominant eigenvalues are proposed in scheme (1).

The OPS controller is introduced into the system, and the gain for each state variable is computed as given in table (4).

The time domain simulations are carried out at nominal loading conditions. Figures (9) and (10) show the system responses (load angle and speed deviation) with 10% step change in mechanical input power (Δp_m) where the coordinated control of PSS and STATCOM C- based controller is compared to individual control. It is clear that the coordinated control of PSS and STATCOM C- based controller greatly improves the system damping compared to their individual control, and the coordinated control solves the problem of low damping when C- based controller is considered.

Scheme (5):

Another way of solving the low damping of STATCOM C – based controller is by coordinated control with STATCOM ψ – based controller. Then, the OPS algorithm is applied to the designed optimal controller that coordinates STATCOM ψ and C– based controllers. The state space equation of this case is the same as that of scheme (1) except the input matrix B is given as:

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & k_{I\psi} & k_F k_{P\psi}/T_F & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & k_{IAC} & k_F k_{PAC}/T_F \end{bmatrix}$$

And

$$U = \begin{bmatrix} U_\psi \\ U_C \end{bmatrix} \quad \text{and} \quad R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The OPS algorithm is used to shift the dominant eigenvalues $(\lambda_1, \lambda_2, \lambda_3 \text{ and } \lambda_4)$ to new location, all the state variable are feedback to the system inputs $(U_\psi \text{ and } U_C)$ through weight factor for each state. The new locations for dominant eigenvalues are proposed in scheme (1).

The OPS controller is introduced into the system, and the gain for each state variable is computed and given in table (5).

To ensure the effectiveness of the proposed controller, time domain simulations with 10% step change in mechanical input power (Δp_m), are performed. The system response of rotor angle ($\Delta\delta$) and speed deviation ($\Delta\omega$) for the above disturbance are shown in figures (11) and (12) respectively. The simulation results obtained clearly indicate that, the proposed coordinated control of ψ – based controller and C – based controller outperform both individual controls. This solves the problem of low effectiveness of individual designs.

6. Conclusions

1. The coordinated controls of PSS and STATCOM devices provide the best means for stabilizing power system, more damping with less effort than individual control. Furthermore, it solves the problem of low effectiveness of individual control.
2. The effectiveness of STATCOM – based controllers in improving the system damping is investigated. The results show that the STATCOM Ψ – based controller provides robust performance, while the STATCOM C – based controller is not effective in providing damping for the system, and the interaction between STATCOM AC and DC voltage controller is overcome through the coordinated control of these controllers.

3.The optimal pole shifting technique makes it possible to directly impose damping constraints in controller design, the benefits are to achieve a simple structure in the damping controller obtained and avoid time-consumption.

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Appendix

System Parameter Values SMIB Equipped with STATCOM

Parameter	*Value*
K_S	1
x_1	0.3
x_2	0.3
ψ_o	46.25
C_{dc}	1
V_{dc}	1
C_o	0.25
x_{SDT}	0.15
t_s	0.5
p_e	0.8
q_e	0.2
k_a	50
t_a	0.05
k_{aci}	0.2
k_{acp}	-0.5
t_{do}	5.04
B	0
G	0
R	0
D	4
M	6
x_d	1
x_d'	0.3

List of symbols

Symbol	**Description**
C_{DC} , V_{DC}	*DC link capacitance and voltage*
ψ	*Phase angle of mid-bus voltage*
δ	*Rotor angle (rad.)*
ω_b	*Synchronous speed (377 rad. /sec.)*
ω	*Rotor speed (rad. /sec.)*
M	*Inertia constant*
P_m	*Mechanical input power of the generator, (W)*

P_e	*Generator electrical output power, (W)*
D	*Machine damping coefficient*
v_d, v_q	*d- and q-axis components of generator terminal voltage(V)*
i_d, i_q	*d- and q-axis components of generator armature current(A)*
$\acute{E}_q$	*Transient generator internal voltage*
x_d	*Synchronous reactance d- axis*
$\acute{x}_d$	*Transient reactance d-axis*
x_q	*Synchronous reactance q- axis*
E_{fd}	*Generator field voltage(V)*
$\acute{T}_{d0}$	*Open-circuit field time constant(sec.)*
K_A	*Gain of excitation system*
T_A	*Time constant of excitation system (sec.)*
v_{ref}	*Reference voltage (V)*
v	*Generator terminal voltage(V)*

U_{pss}	*PSS control signal*
T_W	*Time constant of washout (sec.)*
v_m	*Midpoint voltage(V)*
i_s	*STATCOM current*
v_s	*STATCOM bus voltage(V)*
C	*Magnitude voltage of STATCOM control*
K_{ACP}	*Proportional gain for STATCOM AC voltage*
K_{ACI}	*Integral gain for STATCOM AC voltage*
U_C	*Control signal of STATCOM AC voltage regulator*
U_ψ	*Control signal of STATCOM DC voltage regulator*
K_{DCP}	*Proportional gain for STATCOM DC voltage*

Table (1): Gain associated with each state variable

State control	$\Delta\delta$	$\Delta\omega$	$\Delta E'_q$	ΔE_{fd}	ΔV_{dc}	Δx_1	$\Delta\psi$	Δx_4	ΔC
U_{pss}	0.0742	-42.27	1.232	0.0104	2.134	-9.138	-0.151	43.226	3.585

Table (2): Gain associated with each state variable

State control	$\Delta\delta$	$\Delta\omega$	$\Delta E'_q$	ΔE_{fd}	ΔV_{DC}	Δx_1	$\Delta\psi$	Δx_4	ΔC
U_c	0.3397	-18.79	0.9321	0.0089	05894	0.1972	0.0775	8.2133	2.1986

Table (3): Gain associated with each state variable

State control	$\Delta\delta$	$\Delta\omega$	$\Delta E'_q$	ΔE_{fd}	ΔV_{DC}	Δx_1	$\Delta\psi$	Δx_4	ΔC
U_ψ	48.503	-844.08	85.429	0.922	50.044	13.89	7.633	904.89	1.6059

Table (4): Gain associated with each state variable

State control	$\Delta\delta$	$\Delta\omega$	$\Delta E'_q$	ΔE_{fd}	ΔV_{DC}	Δx_1	$\Delta\psi$	Δx_4	ΔC
U_{PSS}	- 0.0173	- 2.2555	0.046	0.00028	0.0916	0.0173	0.0072	0.5576	0.1625
U_c	-0.044	- 6.4529	0.1261	0.00072	0.1558	0.2185	0.013	1.9065	0.4703

Table (5): Gain associated with each state variable

State control	$\Delta\delta$	$\Delta\omega$	$\Delta E'_q$	ΔE_{fd}	ΔV_{DC}	Δx_1	$\Delta\psi$	Δx_4	ΔC
U_ψ	- 0.0042	- 1.0134	0.0167	0.0007	- 0.0225	0.067	- 0.0014	0.172	0.075
U_c	- 0.0772	- 12.108	0.2255	0.0012	0.1917	0.2325	0.0158	1.711	0.880

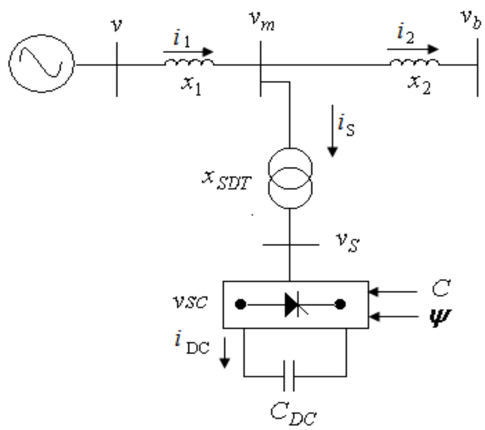

Figure (1): Single machine infinite bus system with a STATCOM

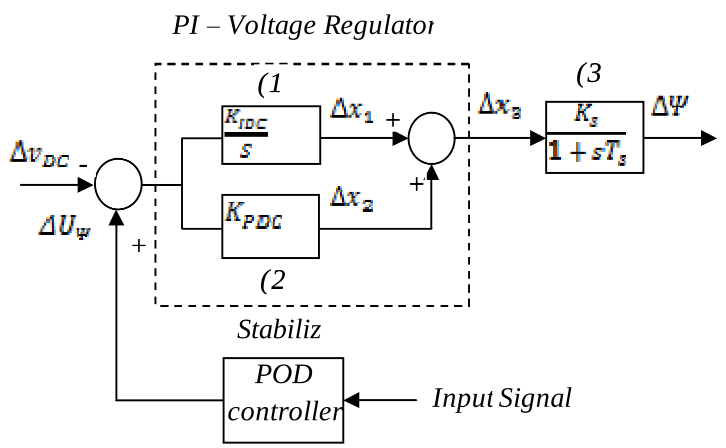

Figure (3): STATCOM dynamic model of DC voltage regulator and OPS stabilizer

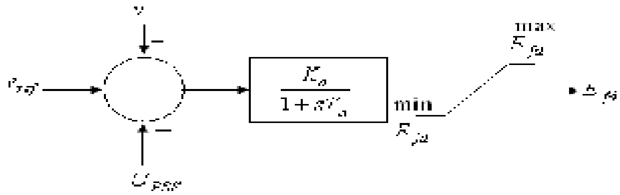

Figure (2): Excitation system block

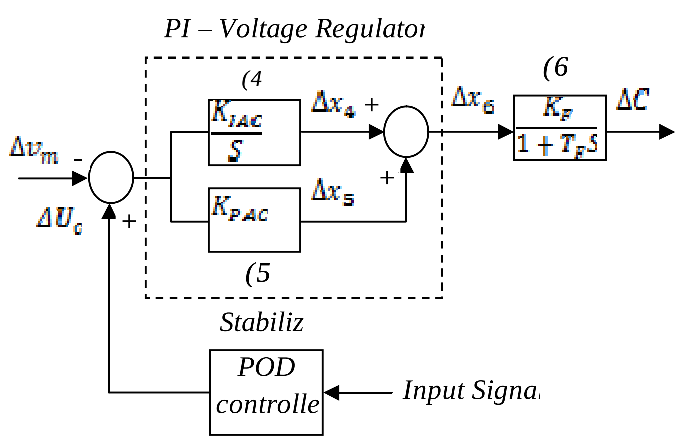

Figure (4): STATCOM dynamic model of AC voltage regulator and POD stabilizer

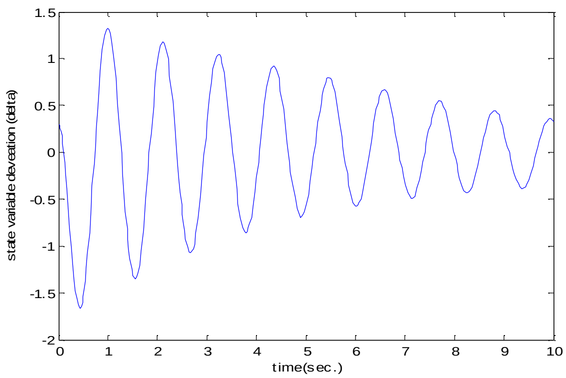

Figure (5): Dynamic response for Δδ without controller

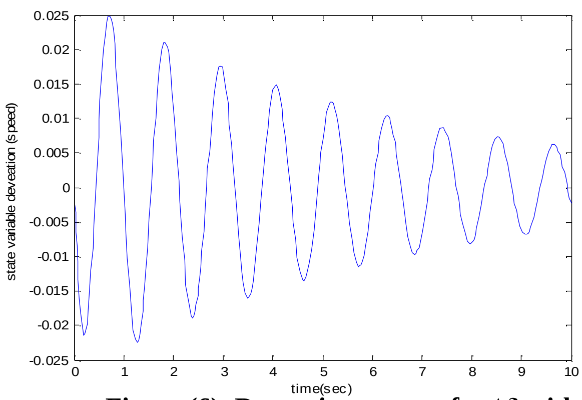

Figure (6): Dynamic response for Δδ with proposed schemes (scheme 1, 3 and 4).

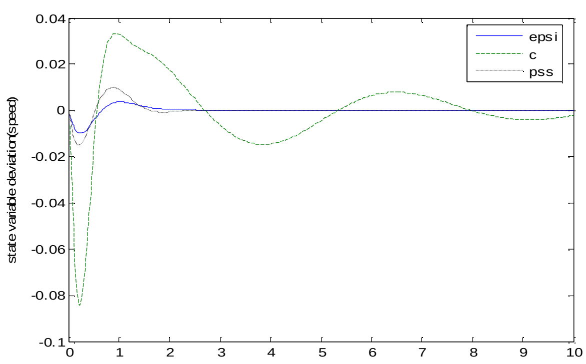

Figure (8): Dynamic response forΔω with proposed schemes (scheme 1, 2 and 3).

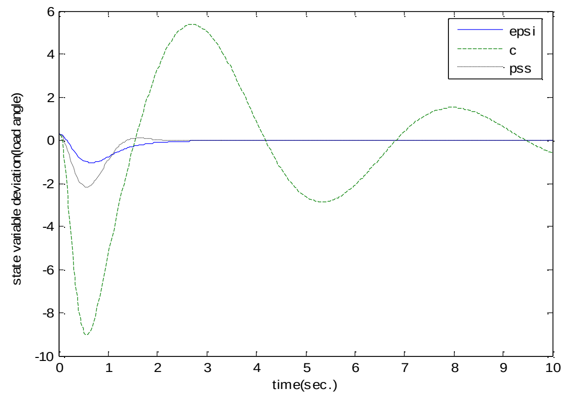

Figure (7): Dynamic response forΔδ with proposed schemes (scheme 1, 2 and 3).

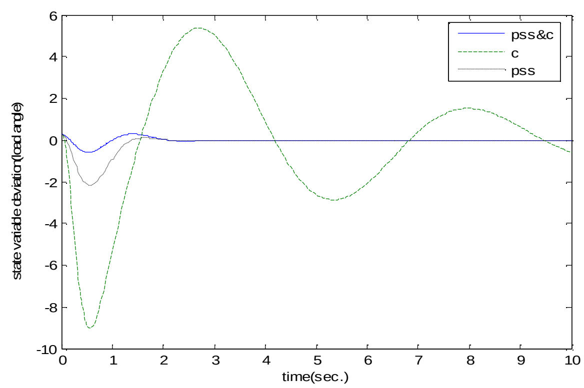

Figure (9): Dynamic response forΔω without controller.

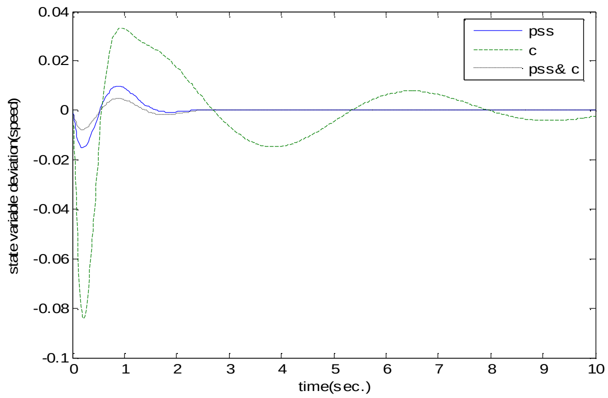

Figure (10): Dynamic response for Δω with proposed schemes (scheme 1, 3 and 4).

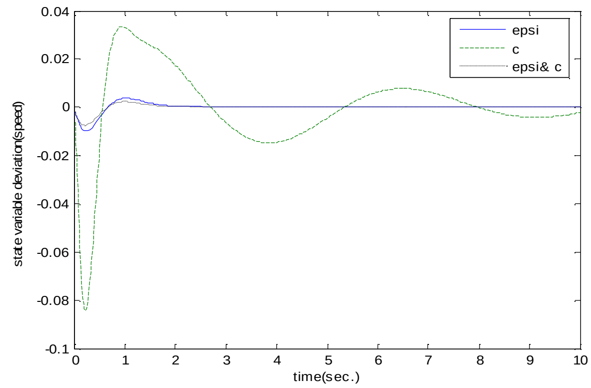

Figure (12): Dynamic response for Δω with proposed schemes (scheme 2, 3 and 5).

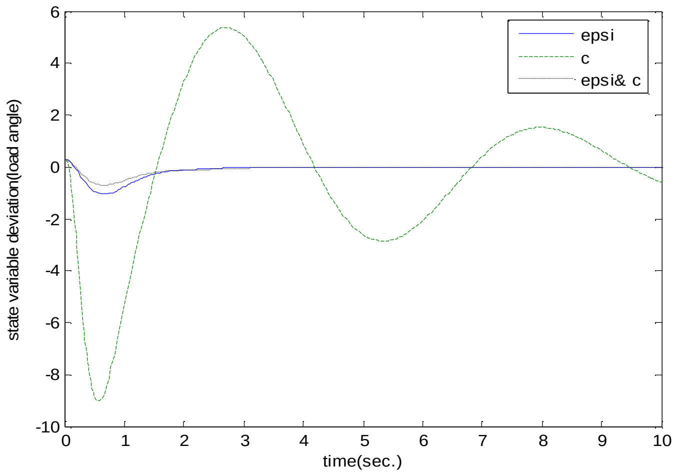

Figure (11): Dynamic response for Δδ with proposed schemes (scheme 2, 3 and 5).