The International Journal Of Engineering And Science (IJES)
|| Volume || 3 || Issue || 7 || Pages || 27-37 || 2014 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

# State Feedback Approaches for Designing A Statcom Supplementary Controller for Oscillations Damping

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**----------------------------------------------ABSTRACT-------------------------------------------------------**

*The authors present a state feedback control approach to the single infinite bus machine and multimachine systems all in-cooperating a static synchronous compensator (STATCOM). The proposed controllers' designs are based on a linear time invariant model of the plant and state feedback scheme. First, the linear mathematical model of STATCOM is derived. Then, using polynomial algorithm and pole placement algorithm, a state feedback control law is derived. The proposed control strategy is tested on two different case studies that is SMIB system and three area five machine system by digital computer simulations using matlab/simulink program for various types of loads and/or disturbances. Comparison of these results with those methods and without controller establishes the elegance of these control approaches.*

***KEYWORDS:*** *Damping controller, ITAE and Low frequency oscillations, STATCOM, and State feedback.*

Date of Submission: 18 December 2013 ⟺ Date of Publication: 20 July 2014

## I. INTRODUCTION

Power system oscillations happen as a result of lack of adequate damping torque at generators' rotors .This situation might happen as a result of a heavy loads in thepower lines, weaker interconnections, very high gain excitation system, sudden and drastic chane in loadse.t.c [1]. The oscillations of the rotor causes some oscillations from other power system variables like transmission line's active and reactive power, voltages at buses, bus frequency and the frequency of the oscillation is usually between 0.1 and 2Hz termed as low frequency[2]. There are types of oscillation: Local mode, Inter area mode, Control mode and Torsional mode of oscillation [3]. devices used as damping controllers for power system oscillation includes static synchronous compensator ( Statcom), power system stabilizers (PSS), High voltage Direct Current(HVDC) links, Thyristor controller series capacitor,(TCSC) etc. PSS is usually used on selected generators for damping local mode oscillation and sometimes used in for inter-area mode oscillation but supplementary controller is much better in inter-area mode oscillation damping when applied to/with the FACTS [4]. Normally the design procedures for these controllers are based on alinearise model under range of different operating points [4-5].

STATCOM is a voltage source converter based FACTS device and shunt connected similar to SVC, that are usually meant for voltage stability and regulation. It is also used for improving power system stability by exchanging reactive power to power networks [6-9]. Study of STATCOM device on voltage and power stability enhancement is done [10]. Liner quadratic regulator (LQR) gives optimalcontrol fora linear system based on a quadratic performance index minimization [11]. Many attentions havebeen put in for investigation and the use ofstate feedback based controllers by different authors such as [12-14].

In this research study, a supplementary state feedback based controller has been tested and proposed for STATCOM. Several Feedback algorithms have been utilized for a few different appropriate operating conditions. Two different case studies have been taken into considerations

[1] Single machine infinite bus and
[2] Multimachine (three area five machine system).

The remain sections of the paper are as follows;

Section ii discussed the statcom compensation model, relevant equations of modeling the Statcom,linescurrents and reactances are derived.

Section iiioverviews the state feedback concepts

Section iv detailed the actual power system model with a Statcom, results and discussions. Then the paper's conclusion was done in Section v

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## II. THEMODELING OF POWER SYSTEM WITH A STATCOM

As seen in Fig. 1.0, a STATCOM is connected to a transmission line via a transformer and it consists of a three phase gate turn-off (GTO) base voltage source converter (VSC) and a Direct Current capacitor. It’s a reactive current source andassumed positive.

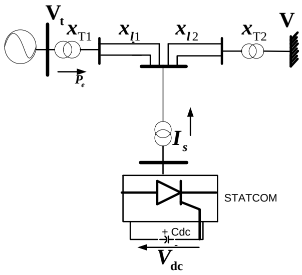


Fig.1 SMIB with STATCOM device

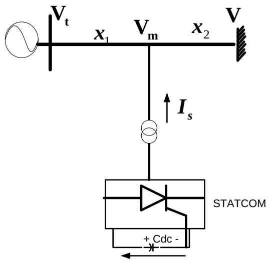


Fig.2 Equivalent SMIB with STATCOM device

$$\dot{I}_s = (K\left(Vref - V\right) - Is)/T$$

Where

$$I_s = I_{sd} + I_{sq} = \left(I_s \cos\theta + jI_s \sin\theta\right) \quad (1)$$

***K*** is again factor.

The voltage difference between the STATCOM bus voltage, $v_L(t)$ and $v_0(t)$ generatesactive and reactive power exchanges between the STATCOM and the power system, that is controlled by adjustment of the voltage magnitude $V_0$ and the phase angle’ $\psi$’ but the two voltages are in same phase so $\psi$ is assumed zero ( $0^0$). STATCOM is installed to maintain AC bus voltage $v_{L(t)}$in the power system and enhances oscillation damping. STATCOM control is implemented through the pulse width modulation(PWM) ratio *m* and phase angle $\psi$ as seen in Fig. 3 below [11],

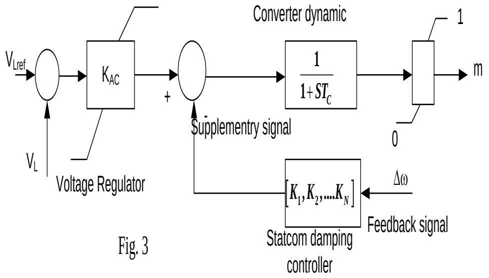


Fig. 3 STATCOM control technique

$$\frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} = \frac{mk}{C_{DC}} I_s \quad (2)$$

From Fig.2,

$$I_2 = I_1 - I_s \quad \bar{V}_t = jx_1\bar{I}_1 + jx_2\bar{I}_2 + \bar{V} \quad (3)$$

Substituting eqn. $I_2$ into eqn. **3** gives

$$\bar{V}_t = jx_1\bar{I}_1 + jx_2(\bar{I}_1 - \bar{I}_s) + \bar{V} = j\left(x_1 + x_2\right)\bar{I}_1 - jx_2\bar{I}_s + \bar{V} \quad (4)$$

That is

$$j\left(x_1 + x_2\right)(I_d + jI_q) = \bar{V}t + jx_2\bar{I}_s - \bar{V}$$

$\Rightarrow j\left(x_1 + x_2\right)(I_d + jI_q) = x_q I_q + (E_q' - x_d' I_d) - jx_2 I_s(\cos\theta + j\sin\theta) - V(\cos\delta + j\sin\delta)$ After expansion and comparism of the real and imaginary parts, the expression of Iq and Id become;.

$$I_d = \frac{E_q' + x_2 I_s \cos\theta - V\sin\delta}{x_1 + x_2 + x_d'} \quad (5)$$

$$I_q = \frac{V\cos\delta + x_2 I_s \sin\theta}{x_1 + x_2 + x_q} \qquad (6)$$

$\bar{V}_m = jx_2 \bar{I}_2 + \bar{V} = \bar{V} + jx_2(\bar{I}_d + j\bar{I}_q - \bar{I}_s) = V_{md} + jV_{mq}$ Therefore

$$V_{md} + jV_{mq} = V(\cos\delta + j\sin\delta) + jx_2\left\{I_d + jI_q - I_s(\cos\theta + j\sin\theta)\right\} \qquad (7)$$

. Substitution ofequation. 5 and equation 6 into equationalso comparing the real and imaginary parts gives us

$$V_{mq} = \frac{(x_1 + x_d')V\cos\delta + E_q' x_2 + I_s \cos\theta\, x_2 (x_1 + x_d')}{x_1 + x_d' + x_2} \qquad (8)$$

$$V_{md} = \frac{(x_1 + x_q)V\sin\delta + I_s \sin\theta\, x_2 (x_1 + x_q)}{x_1 + x_q + x_2} \qquad (9)$$

$$P_e = \frac{E_q' V_m}{x_1 + x_d'}\sin\theta + \frac{V_m^2}{2}\frac{x_d' - x_q}{(x_1 + x_q)(x_1 + x_d')}\sin 2\theta \qquad (10)$$

The dynamics of the generator and the excitation system are expressed as a fourth order model and given as

$$\Delta\dot{\delta} = \omega_b \Delta\omega \qquad (11)$$

$$\Delta\dot{\omega} = -(\Delta P_e + D\Delta\omega)/M \qquad (12)$$

$$\Delta\dot{E}_q' = (-\Delta E_q' + (x_d - x_d')\Delta i_d + \Delta E_{fd})/T_{d0}' \qquad (13)$$

$$\Delta\dot{E}_{fd} = -\frac{K_A}{T_A}\Delta V_t - \frac{1}{T_A}\Delta E_{fd} \qquad (14)$$

$$\dot{I}_s = (K_r \Delta u - \Delta Is)/T \qquad (15)$$

Let the input of STATCOM controller to be;.

$$\Delta u = (V_{ref} - K_u \Delta V_m + K_\omega \Delta\omega) \qquad (16)$$

$K_u$and $K_\omega$are the gains of voltage and damping control loop, respectively, $\boldsymbol{V_{ref}}$is the reference voltage of the STATCOM regulator andKr Gain of the stabilizing signal.
Thus

$$\Delta u = -K_r K_4 K_u \Delta\delta + K_r K_\omega \Delta\omega - K_r K_5 K_u \Delta E_q' - K_r K_6 K_u \Delta I_s \qquad (17)$$

Where $K_1$-$K_{13}$ are linearization constant and brings the system toalinearised power system model in matrix form (18) below

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}_q' \\ \Delta\dot{E}_{fd} \\ \Delta\dot{I}_s \end{bmatrix} = \begin{vmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -K_1 & -D & -K_2 & 0 & -K_3 \\ K_7 & 0 & K_9 & K_{10} & K_8 \\ -K_A K_{11}/T_A & 0 & -K_A K_{13}/T_A & -1/T_A & -K_A K_{12}/T \\ -K_r K_4 K_u/T & K_r K_\omega/T & -K_r K K_u/T & 0 & -(K_r K_6 K_u + 1)/T \end{vmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E_q' \\ \Delta E_{fd} \\ \Delta Is \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ K_r/T \end{bmatrix} Vref \qquad ( \quad (18)$$

## III. STATE FEEDBACK CONTROLLER

***Pole placement with a state feedback***

Assume that the single-input system dynamics are given by
Table 1.0 Butterworth Polynomial factors

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t), \\ y(t) &= Cx(t) + Du(t). \end{aligned} \qquad (19)$$

Assume a control law of the form:

$$u(t) = -Fx(t) \text{ or } u(t) = r(t) - Fx(t) \qquad (20)$$

Is called state feedback and brings system to the form [15]

$$x(t) = (A - BF)x(t) + Br(t),$$
$$y(t) = (C - DF)x(t) + Dr(t) \qquad (21)$$

Closed loop transfer function

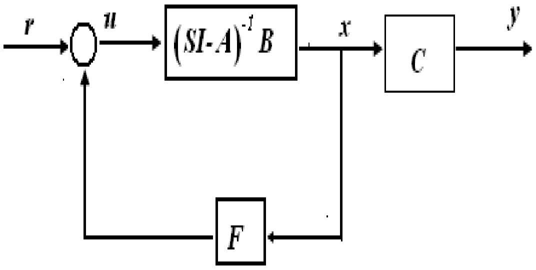


Fig 4.The closed loop control system

We have:

$$x = (SI-A)^{-1}B(r-Fx) \Leftrightarrow sx-Ax= Br-BFx \qquad (22)$$

Therefore, y= Cx, now closed loop transfer function becomes;.

$$s_d(s) = C\ (sI-A_F)^{-1}B \text{ where } A_F = A-BF \quad ,(23)$$

And the Closed loop characteristic polynomial is:

$$x_{cl} = det(sI-A_F) \qquad (24)$$

**In brief**

Assume**(A,B)** are controllable, then for any arbitrary polynomial

$$x_{cl}(s) = s^n + \alpha_{n-1}s^{n-1} + \ldots\ldots + \alpha_1 s + \alpha_0 \qquad (25)$$

There willexist a state feedback gain K, that $x_{cl}(s)$ is closed loop characteristic polynomial, i.e.,

$$x_{cl} = det(sI-A_F) \qquad (26)$$

The matrix $A_F$= (**A-BK**) reveals not only the stability of the closed loop system, but also a response of the rotor angle or speed output. Thus, the controller gain, **K**, matrixmust be designed a such that will meet the stability criteria which will be achieved by means of placing the closed loop poles at a desired locations in the left half of a complex plane. K can therefore be determined using ng:

(1) Equating of equation coefficients
(2) Pole placement algorithms

In this paper the input to STATCOM's controller is taken as Vref and the outputs are taken as from the output of the modeledpower system (rotor speeds, real and reactive powers,rotor angles etc.) eachunder various operating conditions.

### *2. Polynomial Placement Algorithm*

It is from an evidence [15] that with somehigher order systems, ordinary pole placement can become tedious in dealing with, one method for placing poles is by employing the polynomial approximation technique such as**ITAEand** ***Butterworth pattern.***

In these ApproximationsAlgorithms procedure is summarized as: –

- Determining the desired settling time ts –
- Find k = n polynomial from the table1 or 2. –
- Divide the pole locations by ts –
- Form desired characteristic polynomial Φd(s)
- andapply acker/placematlab commands to know the feedback gains. –

Simulate to study the performance and control efforts.

Table 1.0 BUTTERWORTH Polynomial factors

| n | Denominator coefficients for polynomials |
|---|---|
| 1 | $(s + 1)$ |
| 2 | $(s^2 + 1.4142s + 1)$ |
| 3 | $(s + 1)(s^2 + s + 1)$ |
| 4 | $(s^2 + 0.7654s + 1)(s^2 + 1.8478s + 1)$ |
| 5 | $(s + 1)(s^2 + 0.6180s + 1)(s^2 + 1.6180s + 1)$ |
| 6 | $(s^2 + 0.5176s + 1)(s^2 + 1.4142s + 1)(s^2 + 1.9319)$ |
| 7 | $(s + 1)(s^2 + 0.4450s + 1)(s^2 + 1.2470s + 1)(s^2 +$ $1.8019s + 1)$ |

Table 2.0 ITAEPolynomial factors

| |
|---|
| $s^1 + \omega_0^5$ |
| $s^2 + 1.4\omega_0 s + \omega_0^2$ |
| $s^3 + 1.75\omega_0 s^2 + 2.15\omega_0^2 s + \omega_0^3$ |
| $s^4 + 2.1\omega_0 s^3 + 3.4\omega_0^2 s^2 + 2.7\omega_0^3 s + \omega_0^4$ |
| $S^5 + 2.8\omega_0 s^4 + 5\omega_0^2 s^3 + 5.5\omega_0^3 s^2 + 3.4\omega_0^4 s^1 + \omega_0^5$ |
| $S^6 + 3.25\omega_0 s^5 + 6.6\omega_0^2 s^4 + 8.6\omega_0^3 s^3 + 7.45\omega_0^4 s^2$ |
| $+3.95\omega_0^5 s + \omega_0^6$ |
| $S^7 + 4.475\omega_0 s^6 + 10.42\omega_0^2 s^5 + 15.08\omega_0^3 s^4 + 15.54\omega_0^4 s^3$ |
| $+10.64\omega_0^5 s^2 + 4.58\omega_0^6 s + \omega_0^7$ |

## A. Pole placement algorithm

As $K=f V^T$ the elements of F are selected while the process of finding V is as follows [16]:

Let the characteristics equation of the system matrix be $s^n + a_1 s^{n-1} + a_2 s^{n-2} + \dots\dots a_n$

For closed loop purpose ,it is required to move the eigen value of the uncompensated system characteristics equation as soon as eigen value of the closed system $\gamma_1, \gamma_{2,} \gamma_1, \gamma_{2,} \gamma_3 \cdots\cdots \gamma_n$ are specified the desired closed loop characteristics equation is found from

$$P(s)=\prod_{i=1}^{n}(s-\gamma_i)=(s-\gamma_1)(s-\gamma_2)\dots\dots\dots(s-\gamma_n) \qquad (28)$$

The difference between the open-loop Xtics polynomial and that of the desired closed loop Xtics polynomial is D .

$$D(s)=P(s)-A(s) \qquad (29)$$

$$D(s)=(p-a_1)s^{n-1}+(p-a_2)s^{n-2}+\dots\dots\dots(p-a_n) \qquad (30)$$

Then we defined a vector d whose element the coefficient are of $D(s)$

$$d=\left[(p_1-a_1),(p_2-a_2)\dots\dots\dots(p_n-a_n)\right] \qquad (31)$$

Select a vector F such that the element of the matrix

$$Q=\left[BF;ABF;A^2BF\dots\dots\dots A^{n-1}BF\right] \qquad (32)$$

Is completely state controllable, then the vector V can be found as

$$V = Q^{-1} X^{-1} d^{T} \tag{33}$$

Where X is a Toeplitz matrix defined as

$$X = \begin{bmatrix} 1 & 0 & 0 & 0 \\ a_1 & 1 & 0 & 0 \\ a_2 & a_1 & 0 & 0 \\ . & . & . & . \\ . & . & . & \\ a_{n-1} & a_{n-2} & . & 1 \end{bmatrix} \tag{34}$$

### B. PID-STATCOM Pole Placement Approach

In the design of the PID controller, the gain settings can be computed by placing the Eigen values at a pre-specified locations, this is usually known as the pole placement method where $K_{p,}$ $K_{I,}$ $K_{D,}$ are the gains of the PID controller and $T_W$ is the wash out time constant as shown in fig 3,

The approach starts with linearizing the non-linear model around a nominal point to obtain the desired linearized model described by input-output equations

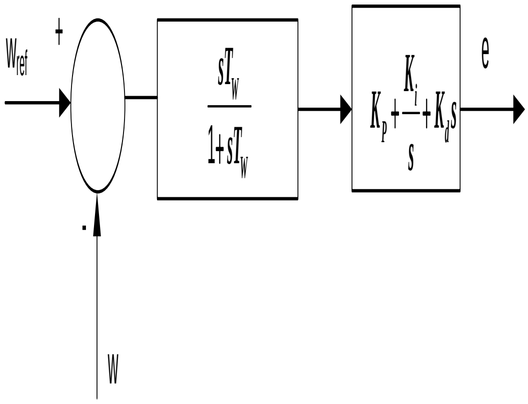


Fig.5 The magnitude control block diagram

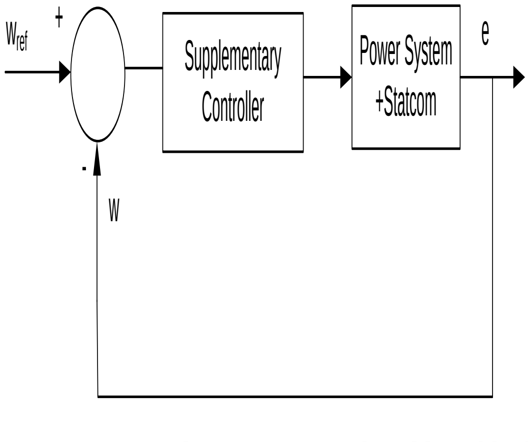


Fig. 6 PID-STATCOM Based power system closed loop block diagram

$$x^{\dot{}}(t) = Ax(t) + Bu(t), \qquad (35)$$
$$y(t) = Cx(t) + Du(t) \qquad (36)$$

Where x, y and u are the state vector variables, output signal and control signal respectively, taking the Laplace transform and substituting the output equations into the state equation gives

$$X(s) = (sI - A)^{-1}\mathrm{BU(s)} \qquad (37)$$

If the system output Y is fed into the input of the PID controller as shown in fig 4, and the PID controller is having a transfer function H(s), we can therefore write the control signal as

U(s)=H(s)Y(s) where

$$H(s) = \frac{\mathrm{sT_w}}{\mathrm{1+sT_w}}\ (\mathrm{k_p} + \frac{\mathrm{K_i}}{\mathrm{S}} + \mathrm{k_{ds}}) \qquad (38)$$

Putting (38) into (37), we have:

$$X(s) = (sI - A)^{-1}\mathrm{B}H(s)\mathrm{C}X(s)(39)$$

Or

$$[1 - (sI - A)^{-1}\mathrm{B}H(s)\mathrm{C}]\,X(s) = 0 \qquad (40)$$

If λ is the assigned Eigen value of the whole closed loop system, then

$$\mathrm{Det}[1 - (\lambda I - A)^{-1}\mathrm{B}H(\lambda)\mathrm{C} = 0 \qquad (41)$$

Equ.15 can be re-written as

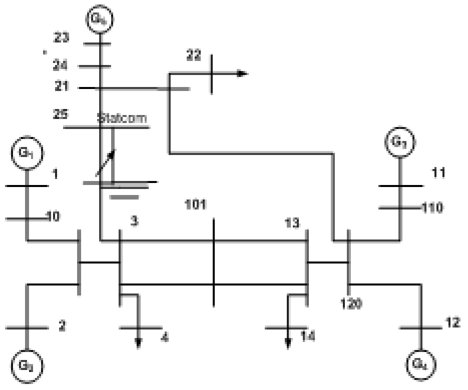
$$1 - C(\lambda I - A)^{-1}\mathrm{B}H(\lambda) = 0 \qquad (42)$$

or

$$H(\lambda) = \frac{1}{1 - C(\lambda I - A)^{-1}\mathrm{B}} \qquad (43)$$

Equ. 38=Equ.43, thus

$$\frac{\lambda \mathrm{T_w}}{1+\lambda \mathrm{T_w}}\mathrm{k_p} + \frac{\mathrm{T_w}}{1+\lambda \mathrm{T_w}}\mathrm{k_i} + \frac{\lambda^2 \mathrm{T_w}}{1+\lambda \mathrm{T_w}}\mathrm{k_d} = \frac{1}{1 - C(\lambda I - A)^{-1}\mathrm{B}}(44)$$



### 4.1 Three Area Five machine system. with STATCOM

## IV. RESULTS AND DISCUSSION

**T**he effectiveness of the proposed methods was tested on two case studies

(1) Single machine infinite bus system.
(2) Three Area five machine system

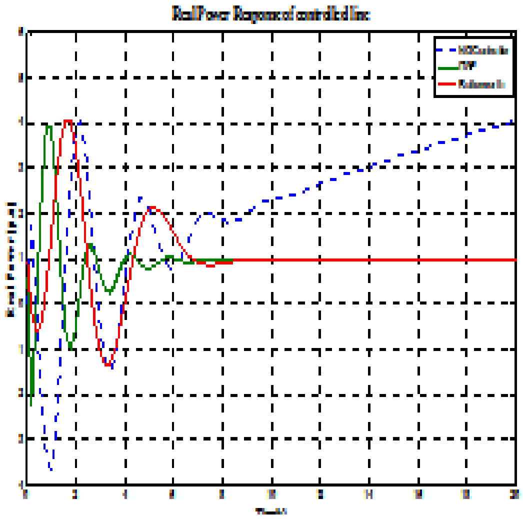


Fig.11 Real power response

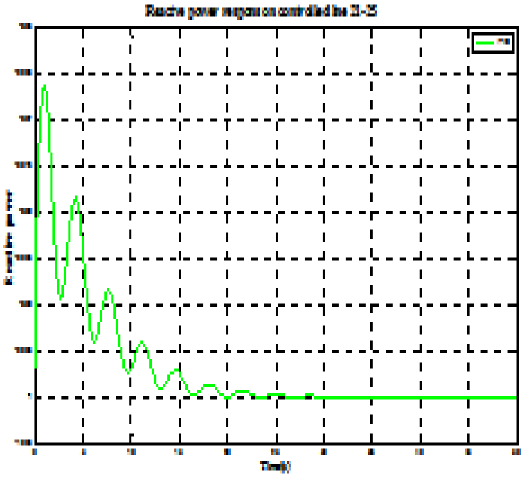
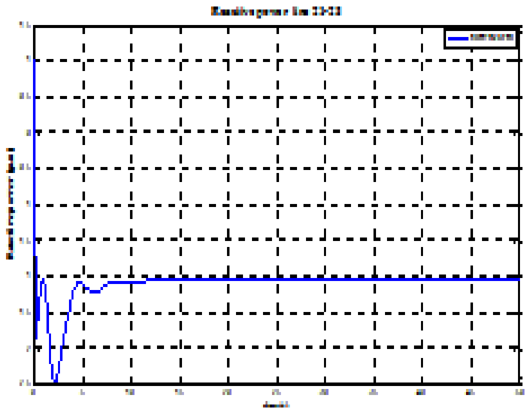


Fig.12 reactive power for line 21-25 using ITAE controller



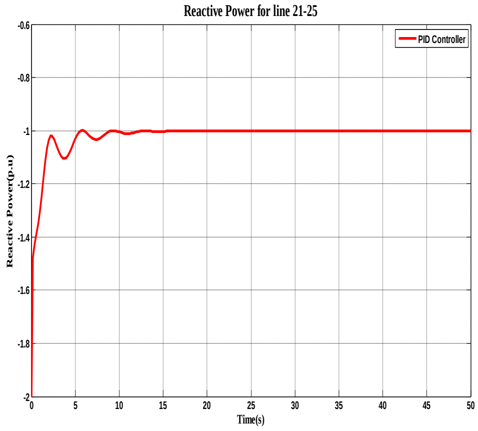


Fig.8 Reactive Power for m=line 11to 5

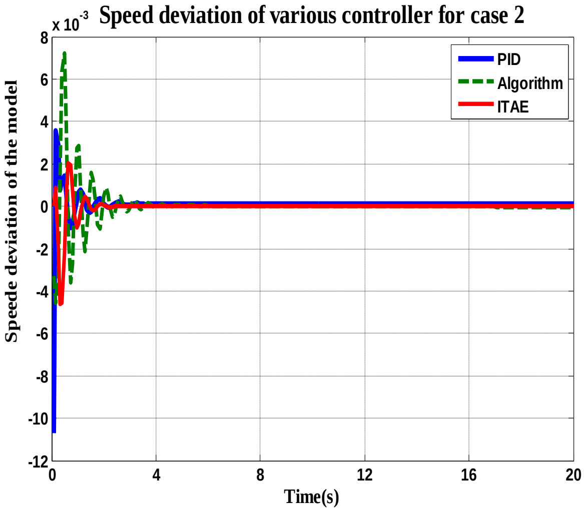


Fig.9 Speed deviation of case2

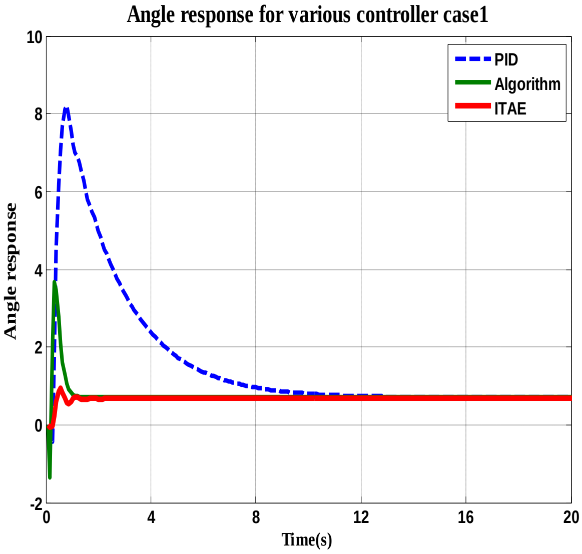


Fig.10 angle respone of case 12

To assess the effectiveness of the proposed methods, two different loading conditions are considered which name case1 and case 2. The results for the systems are presented in what follows:
Case 1 (normal loading): Operating points of SIMB= Pe=1.0pu at unity pf.; Vt=1.0 p.u.
Case 2 (heavy loading): Operating points of SIMB= Pe=1.2pu at 0.8 pf.; Vt=1.2 pu.
multi-machine power systems stability enhancement by means of STATCOM-based stabilizers was studied. To demonstrate the influence of the introduction of STATCOM [28] to the multi machine power systems,The three-area five machine system model shown in Fig. 8, is used, the STATCOM is inserted between buses 21 and 25. The voltage at bus 21 and reactive power flow into bus 25 is controlled is controlled by the statcom element. Generators 1 to 4 have static exciters with power system stabilizers, and generator 5 has a dc exciter. Each generator has a thermal turbine with governor. There is one under damped low frequency electro-mechanical mode in which generator 5 oscillates against generators 1 to 4
A comparison of the responses obtained by the three proposed method based on pole placement techniques,
PID controller tuning based on pole-placement technique produce optimum controller functions for linear systems designed for case 1 and case 2 operating points. By assigning three poles of the compensated closed loop system the appropriate values of $K_P$, $K_I$ and $K_D$ has been obtained. The location of the dominant eigenvalues were selected to be $-1.8561 \pm j8.2953$, corresponding to the damping ratio of 0.2186, the PID controller parameter for the nominal operating point(case 1) is obtained to be: KP=-4.95; KI=-296.3 and
KD=113.23. While for pole algorithm described in section 3 the controller parameter are obtained as [K1, K2, K3, K4, K5] = [-0.9680 63.7854 -27.6727 -0.1683 0.1585]. For ITAE
While for ts=5s , we have $-1.6054, -0.8672 \pm j\,1.7504, -1.3143 \pm j\,1.1357, -1.5365 \pm j\,0.5616i$
The ITAE controller parameter are obtained as [$K_1$, $K_2$, $K_3$, $K_4$, $K_{5,}$ K6, K7] = [32.9, -9.2,420.9,-18.2,2660,-4058,-1066]. Figure 10 shows the response of real power in line 21-25 where statcom is injecting reactive power from bus 25 for different algorithm based on pole placement. Figure 12-13 shows the response for reactive for ITAE, Butterworth and PID
controller. Figure 11 demonstrates the voltage response of bus 25 where the statcom is connected while figure 12 shows the speed deviation of (G1-G3) response under different control algorithm.

## V. CONCLUSIONS

In this paper, STATCOM Controller based on state feedback concepts are proposed for damping oscillations and the effectiveness of the proposed control methods are compared within themselves under some disturbances. The controllers are tested on single machine infinite bus System From the The

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desired poles for 7th order reduction are-8.0271, $-4.3361 \pm j8.7519$, $-6.5714 \pm j5.6786$, $-7.6824 \pm j2.8081$

results it can be concluded that the state feedback based on ITAE produces no steady state error and acceptable overshoot under some disturbances.

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