# Improving the AGC Performance of an Interconnected Multi-unit Power System using FACTS Devices

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***Abstract* – An interconnected power system is subjected to load disturbances with rapid change, system frequency may be severely affected and becomes oscillatory. To compensate for such load disturbances and to stabilize the frequency oscillations, the dynamic power flow control of the FACTS devices located in series with the tie line between interconnected power systems, are employed. In this paper an attempt has been made to understand the dynamic performance of Automatic Generation Control (AGC) of a two area multi-unit hydro–thermal power system with Static Synchronous Series Compensator (SSSC) and Thyristor Controlled Phase Shifter (TCPS). The optimal values of the AGC loop integral gain settings are obtained using integral squared error (ISE) technique following a step load disturbance in either of the areas by minimizing a quadratic performance index. Time domain simulations were carried out to study the performance of the power system with SSSC and TCPS and results are discussed.**

***Keywords: AGC; SSSC; TCPS; LFC; Hydro-thermal system.***

## I. Introduction

In modern power system network, there are number of generating utilities like hydro, thermal, gas and nuclear power generation and are interconnected together through tie-lines to provide secure and economical operation. These interconnections include control areas of different generating units. For the successful operation of interconnected power systems, the matching of total generation with total load demand and associated system losses is required. This matching between load and generation is achieved by Automatic Generation Control (AGC). Apart from matching the generation with demand, the AGC will maintain the power interchange between the interconnected areas within specified limits.

Automatic Generation Control scheme has two main control loops namely, primary control and secondary control .During load variation, the primary controller with the help of speed governor adjusts the generation to match the demand. Secondary controllers are designed to regulate the area control errors to zero effectively. As an interconnected power system is subjected to a large load change, conventional frequency control, i.e. governor, may not be rapidly able to damp large frequency oscillation due to its slow response. To overcome this problem, a high speed response compensator should be used [1].

Due to fast operation of Flexible AC Transmission System (FACTS) devices, they are used in most fields of power system such as power flow control, improvement of transient stability and power oscillation damping. Static Synchronous Series Compensator (SSSC) is one of the important members of FACTS family [3] which can be installed in series with the transmission lines. With the capability to change its reactance characteristic from capacitive to inductive, the SSSC is very effective in controlling power flow. Ngamroo et al. [4] proposed the application of SSSC for frequency stabilization by locating SSSC in series with the tie-line between interconnected two-area power systems with thermal units.

Thyristor control phase shifter (TCPS) is another FACTS device installed in series with the tie-line, which changes the relative phase angle between the system voltages. Therefore the real power transfer between interconnected power systems can be regulated. Das et al. [5] investigated the application of Thyristor Controlled Phase Shifters (TCPS) as a new ancillary service for the stabilization of frequency oscillations of an interconnected single unit hydro-thermal power system.

The critical literature survey of AGC based on both linear and non linear model is presented in [6]. Literature survey shows that most of the earlier works in the area of AGC pertain to interconnected single unit hydro-thermal systems or thermal systems with non reheat type turbines and relatively lesser attention has been devoted to the AGC of interconnected multi-unit hydro-thermal system with reheat type turbines. The paper [7] is discussed the performance of the AGC with respect to the change of system parameters. AGC can be done in a distributed energy management systems too [8]. Also most of the works concerned with AGC of interconnected power system pertains to tie-line bias control strategy [9-15]. In view of the above, the main objectives of the present work were:

- To develop a linearised model of an interconnected two-area multi-unit hydro-thermal system for AGC study and investigate its dynamic performance after the small load perturbation.

- To compare the dynamic responses of two-area multi-unit hydro-thermal system with and without considering SSSC and TCPS.
- To determine the optimum values of integral gain settings in the control areas.

## II. Power System Model

The AGC system introduced in this work consists of an interconnection of two generating areas. Area 1 comprises of two hydraulic generation units and area 2 consists of two thermal generating units. The detailed transfer function models of speed governors and turbines are discussed and developed in the IEEE Committee Report on Dynamic models for Steam and Hydro Turbines in Power System Studies [10]. The dynamic behaviour of the boiler's model is expressed in [9]. Area participation factors (apf) are also considered as the system under investigation is a multi unit two area system; apf's are the ratios in which generating units adjust their power output. It is noted that in area 1, $apf_{11}$+ $apf_{12}$ = 1 and in area 2, $apf_{21}$+$apf_{22}$ =1. Here $apf_{11}$ = 0.6, $apf_{12}$ = 0.4, $apf_{21}$ =0.55 and $apf_{22}$ = 0.45 has been chosen. The detailed transfer function block diagram model of the two-area multi-unit hydro-thermal system is shown in Fig. 1.

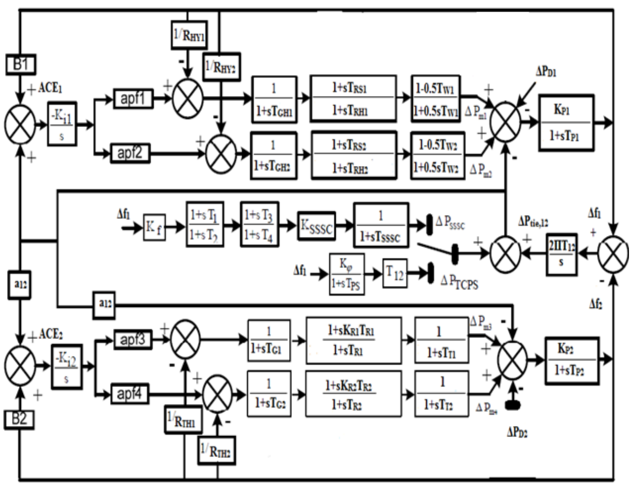


Fig.1 Block diagram of two area multi unit hydro thermal power systems.

A step load perturbation of 1% of the nominal loading is considered in either of the areas. Nominal parameters of the system are taken from the references.

The two-area multi unit interconnected hydrothermal power system linearised around an operating reference point can be described by the standard state space equation as

$$\dot{X} = AX + BU + \Gamma P \quad (1)$$

where X, U and P are the state, control and disturbance vectors respectively and A, B and Γ are real constant matrices of appropriate dimensions which in turn depend on the system parameters and the operating point.

$$X = [\Delta f_1, \Delta P_{g1}, \Delta P_{r1}, \Delta P_{t1}, \Delta P_{g2}, \Delta P_{r2}, \Delta P_{t2}, \Delta f_2, \Delta P_{g3}, \Delta P_{r3}, \Delta P_{t3}, \Delta P_{g4}, \Delta P_{r4}, \Delta P_{t4}, \Delta P_{tie12}]^T \quad (2)$$

$$U = [u_1, u_2]^T \quad (3)$$

$$P = [\Delta P_{d1}, \Delta P_{d2}]^T \quad (4)$$

where

$\Delta f_i$ – Frequency deviation of area i

u – Control variable

$\Delta P_{di}$ – Incremental load demand at area i

$\Delta P_{gi}$ – Incremental change in generator power output of area i

$\Delta P_{ri}$ – Incremental change in turbine power output of area i

$\Delta P_{ti}$ – Incremental change in governor power output of area i

$\Delta P_{tie}$ – Tie-line power deviation between two areas

## III. Modeling of SSSC

A Static Synchronous Series Compensator employs self-commutated voltage-source switching converters to synthesize a three-phase voltage in quadrature with the line current, emulates an inductive or a capacitive reactance so as to influence the power flow in the transmission lines [13]. The magnitude and polarity of injected voltage, $V_q$ are the two factors for dynamically controlling compensation level. The device is in dual mode of capacitive and inductive. The schematic of SSSC, located in series with the tie−line between the interconnected areas can be applied to stabilize the area frequency oscillations as shown in Fig.2. The equivalent circuit of this system can also be represented by voltage source $V_s$ in series with a transformer leakage reactance $X_s$. The voltage source $V_s$ is the controllable factor of SSSC that actually represents the magnitude of injected voltage. Fig.3 demonstrates the phasor diagram of the system considering the operating conditions of SSSC.

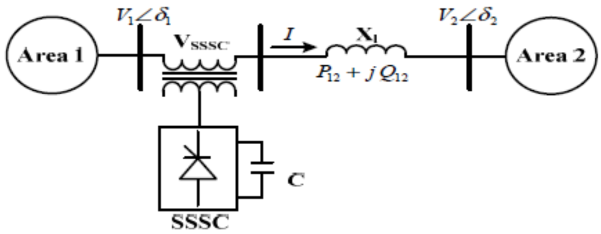


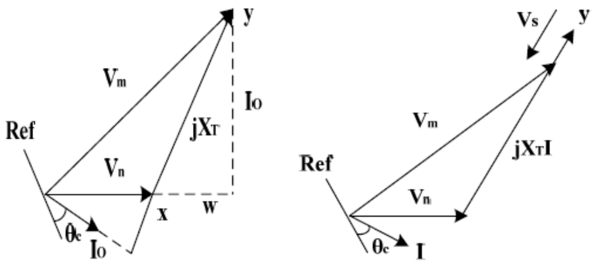

Fig.2 Schematic of interconnected two-area power system with SSSC in series with tie-line.

When $V_s = 0$ , the current $I_0$ of the system is given by

$$I_0 = \frac{V_m - V_n}{jX_T} \tag{5}$$

where $X_T=X_L+X_S$. The angle of the current is given by

$$\theta_C = \tan^{-1}\left[\frac{V_n \cos\theta_n - V_m \cos\theta_m}{V_m \sin\theta_m - V_n \sin\theta_n}\right] \tag{6}$$




(a) (b)

Fig.3 Phasor diagram (a) $V_s$= 0 (b) $V_s$ lagging I by $90^0$.

From Fig.3 (b), eqn.(5) can be generalized as

$$I = \frac{V_m - V_s - V_n}{jX_T} = \left[\frac{V_m - V_n}{jX_T}\right] + \left[\frac{-V_s}{jX_T}\right] = I_0 + \Delta I \tag{7}$$

The term $\Delta I$ is an additional current term due to the SSSC voltage $V_s$. The power flow from bus m to bus n can be written as

$$S_{mn} = V_m I^* = S_{mno} + \Delta S_{mn} \tag{8}$$
$$P_{mn} + jQ_{mn} = (P_{mno} + \Delta P_{mn}) + j(Q_{mno} + \Delta Q_{mn})$$

where $P_{mn0}$ and $Q_{mno}$ are the real and reactive power flows respectively when $V_s = 0$. The change in real power flow caused by the SSSC voltage $V_s$ is given by

$$\Delta P_{mn} = \frac{V_m V_s}{X_T} \sin(\theta_m - \alpha) \tag{9}$$

When $V_s$ lags the current by $90^0$ ($\alpha = \theta_c - 90^0$), $\Delta P_{mn}$ can be written as follows

$$\Delta P_{mn} = \frac{V_m V_s}{X_T} \cos(\theta_m - \theta_c) \tag{10}$$

From eqn.(6), the term cos ($\theta_m - \theta_c$) in (10) can be written as

$$\cos(\theta_m - \theta_c) = \frac{V_n}{V_m} \cos(\theta_n - \theta_c) \tag{11}$$

Referring to fig.3(a), we have

$$\cos(\theta_n - \theta_c) = \frac{yw}{xy} \tag{12}$$

and it can be seen that

$$yw = V_m \sin(\theta_{mn}) \tag{13}$$

$$xy = \sqrt{V_m^2 + V_n^2 - 2V_m V_n \cos\theta_{mn}} \tag{14}$$

and $\theta_{mn} = \theta_m - \theta_n$. Using the above relationship, the term $\Delta P_{mn}$ can be expressed as

$$\Delta P_{mn} = \frac{V_m V_n}{X_T} \sin\theta_{mn} \times \frac{V_s}{\sqrt{V_m^2 + V_n^2 - 2V_m V_n \cos\theta_{mn}}} \tag{15}$$

From eqn. (8), it can be written as $P_{mn} = P_{mn0} + \Delta P_{mn}$ which implies

$$P_{mn} = \frac{V_m V_n}{X_T} \sin\theta_{mn} + \left[\frac{V_m V_n}{X_T} \sin\theta_{mn} \times \frac{V_s}{\sqrt{V_m^2 + V_n^2 - 2V_m V_n \cos\theta_{mn}}}\right] \tag{16}$$

Linearizing eqn.(16) about an operating point

$$\Delta \dot{P}_{mn} = \frac{V_m V_n}{X_T} \cos(\theta_m - \theta_n)(\Delta\theta_m - \Delta\theta_n)$$
$$+\left[\frac{V_m V_n}{X_T} \sin\theta_{mn} \times \frac{1_s}{\sqrt{V_m^2 + V_n^2 - 2V_m V_n \cos\theta_{mn}}} \Delta V_s\right] \tag{17}$$

The controller to change the SSSC voltage can be represented as:

$$\Delta V_s = \left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)\left(\frac{K_2}{1+Tsssc}\right)\Delta Error$$

Therefore eqn.(17) becomes

$$\Delta \dot{P}_{mn}(s) = \frac{T_{mn}}{s}[\Delta f_m(s) - \Delta f_n(s)] \tag{18}$$
$$+ K_f \left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)\left(\frac{K_{SSSC}}{1+sT_{SSSC}}\right)\Delta f_1(s)$$

where $K_{SSSC}=K_1K_2$ and $K_f$ equal to nominal system frequency. Hence $\Delta P_{mn}= \Delta P_{tie}+ \Delta P_{SSSC}$ implies

$$\Delta P_{SSSC} = \frac{V_m V_n}{X_T}\sin\theta_{mn} \times \frac{\Delta V_s}{\sqrt{V_m^{\,2} + V_n^{\,2} - 2V_m V_n \cos\theta_{mn}}} \tag{19}$$

As stated in eqn. (18), it is clear that variations in the SSSC voltage $\Delta V_s$ result in the controlling of SSSC's power which will consequently control the frequency and tie line deviations. The frequency deviation of area 1 would act as input of the SSSC device [16]. The structure of SSSC for the frequency stabilization consists of two gain blocks with gain $K_f$ equal to nominal frequency and $K_{SSSC}$, a proportional block with the time constant of $T_{SSSC}$ and two stage phase compensation blocks as shown in fig.4. The phase compensation block with time constants $T_1$, $T_2$, $T_3$ and $T_4$ provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals.

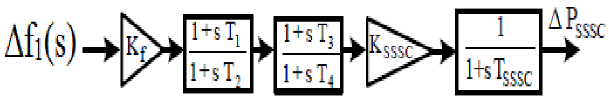



Fig.4 Structure of SSSC as a frequency controller

## IV. Modeling of TCPS

Fig. 5 shows a two‐area multi-unit hydro-thermal interconnected system assuming TCPS in series with the tie‐line. Area 1 is the hydro one comprising two units is followed by TCPS. Second area is the thermal one consisting of two reheat units. The incremental tie‐line power flow from first area to second one with TCPS is expressed as eqn. (20).

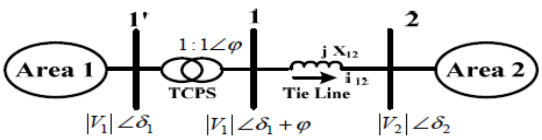



Fig.5 Schematic of interconnected two-area power system with TCPS in series with tie-line

The phase shifter angle $\Delta\varphi(s)$ can be written as:

$$\Delta\phi(s) = \frac{K_\phi}{1 + sT_{PS}}\Delta Error_1(s) \tag{20}$$

where $K_\varphi$ and $T_{PS}$ are the gain and time constants of the TCPS and $\Delta Error_1(s)$ is the control signal which controls the phase angle of the phase shifter [17]. $\Delta Error_1$ can be any signal such as the hydro area frequency deviation $\Delta f_1$ or the area control error (ACE) of the hydro area $ACE_1$ (i.e. $\Delta Error_1 = \Delta f_1$ or $ACE_1$) to the TCPS unit to control the TCPS phase shifter angle which in turn controls the tie-line power flow. Thus, with $\Delta Error_1 = \Delta f_1$.Therefore, it can be written as:

$$\Delta P_{tie12}(s) = \frac{2\prod T_{12}}{s}[\Delta f_1(s) - \Delta f_2(s)] + T_{12}\Delta\phi(s) \tag{21}$$

However, from the practical point of view, as TCPS is placed near Area 1, measurement of $\Delta f_1$ will be easier rather than $ACE_1$, which requires measurement of tie-power also. Hence, in the present work, the frequency deviation of the thermal area $\Delta f_1$ is chosen as the control signal. The structure of TCPS as a frequency controller is shown in fig.6.

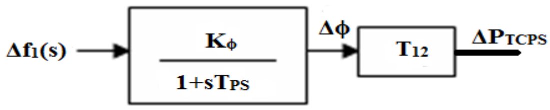



Fig.6 Structure of TCPS as a frequency controller.

## V. Parameter Optimization

Integral Squared Error (ISE) technique is used for obtaining the optimum gain settings of the integral controllers. A characteristic of the ISE criterion is that, it weighs large errors heavily and small errors lightly. A quadratic performance index (J) is given by

$$J = \int_0^t (\Delta f_1^{\,2} + \Delta f_2^{\,2} + \Delta P_{tie\,12}^{\,2})dt \tag{22}$$

Its value is minimized for 1% step load disturbance in either of the areas for obtaining the optimum values of the integral gain settings. Optimal values are those corresponding to the minimum of the performance index. The optimum value of the gain settings can be obtained on an individual basis by considering the other area uncontrolled [18].

## VI. Simulation Results and Discussion

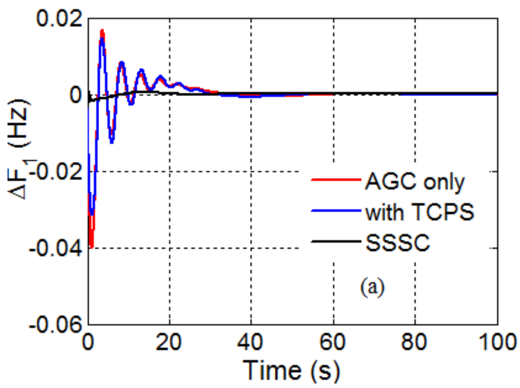
Time domain simulation studies have been carried on an interconnected two-area multiunit hydro-hydro and thermal-thermal system with and without FACTS devices after 1% step load perturbation in either of the areas. Fig.7 gives the dynamic responses for the hydro and thermal area frequency deviations and inter-area tie-power oscillations. It can be observed that, the transient behaviour of area frequencies and tie-power have improved significantly in terms of peak deviations, number of oscillations and settling time in the presence of SSSC and TCPS.

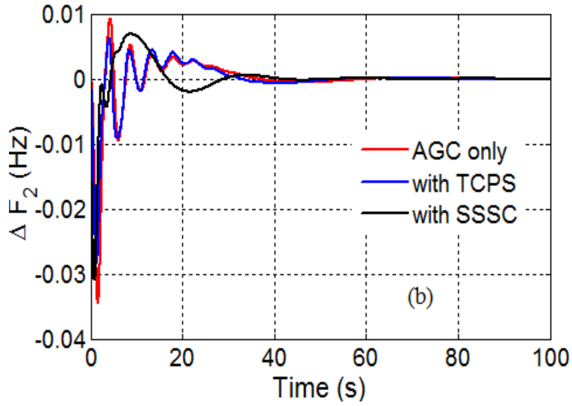
Fig.7a. gives the frequency deviation response $\Delta f_1$ with AGC alone, with TCPS and with SSSC in series with the tie-line near area1. It can be observed that frequency deviation response have improved significantly using SSSC. The initial oscillations have been effectively reduced with TCPS. It also shows that AGC, TCPS and SSSC are settling around 35s. By comparing both of these device performances, the SSSC improves the system performances by reducing the oscillations.

Figs. 7b and 7c give the frequency deviation response $\Delta f_2$ and inter- area tie-power oscillations $\Delta P_{tie}$ with TCPS, SSSC in series with the tie-line near area1. It could be observed that frequency deviation response and tie-line oscillations have improved significantly using SSSC. These small oscillations in the tie line introduce the power losses at the initial stages which have been avoided in the system with SSSC. SSSC improves the oscillations at the initial responses but the settling time for all the cases remain around 40s. The incorporation of a single SSSC in series with the tie-line damped out the frequency and tie-line power deviations can give more consistent results.

The generation responses for both the hydro ($\Delta P_{g1}$, $\Delta P_{g2}$) and thermal areas ($\Delta P_{g3}$, $\Delta P_{g4}$) are observed under the 1% step load disturbance in area1 which are shown by Figs. 8a,8b and 8c & 8d respectively. From those figures it could be noted that, as the step load disturbance has occurred in area1, the hydro unit should adjust its output at the earliest, so as to take up the local load perturbation in its area as per its obligation as reflected in Figs. 8a and 8b. Further, as per the approved practices of interconnected operations, area 2 need not contribute to the local load fluctuation in area 1 and hence should settle down to steady state value of zero as early as possible and this were reflected in Figs. 8c and 8d. It may be noted that the initial negative deflection of the transient response of the output of the hydro unit is attributed to water hammer effect.

As the load disturbance has occurred in area 1, at steady state, the power generated by generating units in area 1 are in proportion to the ACE participation factors. Therefore, as in Fig.8, at steady state, $\Delta P_{g1} = \Delta P_{D1} \times apf11 = 0.01 \times 0.6$



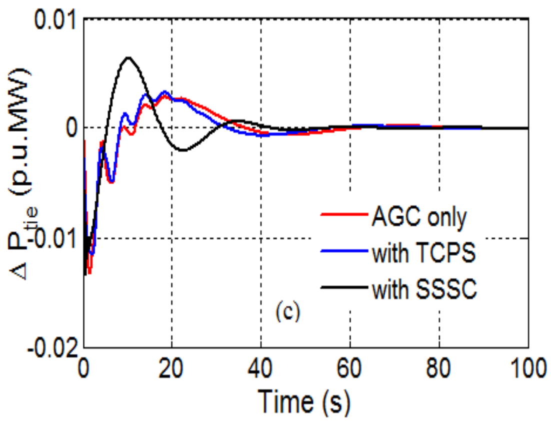
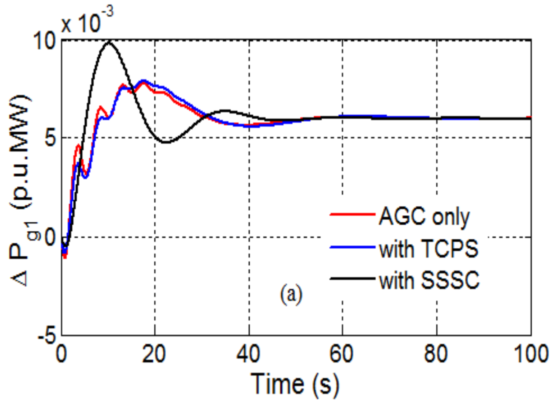




Fig.7(a),(b)&(c). Dynamic responses for $\Delta f_1$ , $\Delta f_2$ ,$\Delta Ptie_{12}$ with 1% step load disturbance in area1.



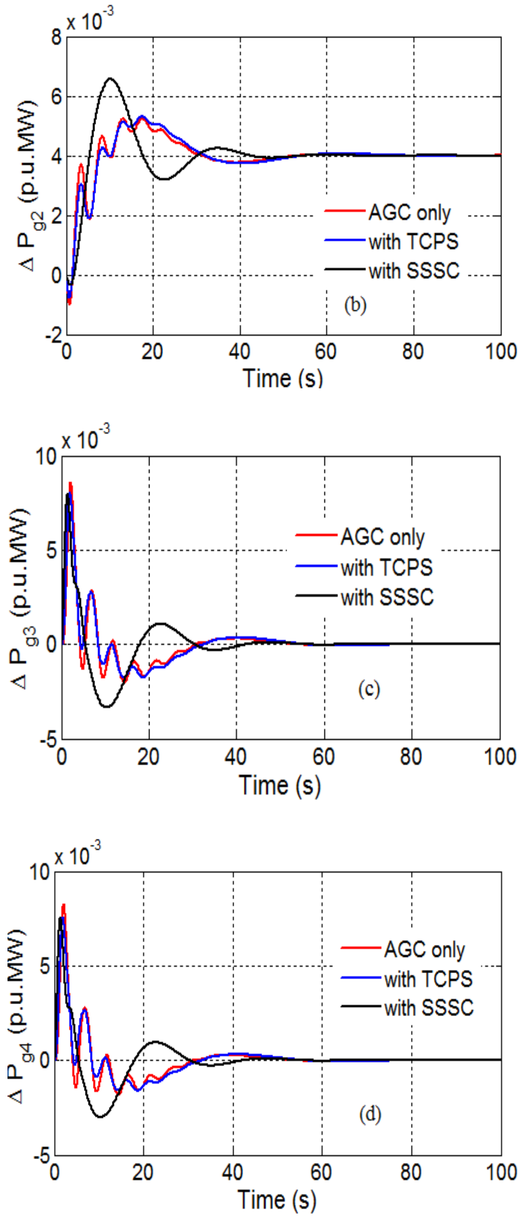



Fig.8 (a), (b), (c),&(d) Dynamic responses for $\Delta P_{g1}$, $\Delta P_{g2}$, $\Delta P_{g3}$ & $\Delta P_{g4}$ with 1% step load disturbance in area1.

=0.006 p.u. MW and $\Delta P_{g2} = \Delta P_{D1} \times apf12 = 0.01 \times 0.4 = 0.004$ p.u. MW. Similarly $\Delta P_{g3} = \Delta P_{D2} \times apf21 = 0 \times 0.55 = 0$ p.u.MW and $\Delta P_{g4} = \Delta P_{D2} \times apf21 = 0 \times 0.45 = 0$ p.u. MW at steady state. Hence, from Figs. 7 and 8, it could be observed that system with SSSC have improved the dynamic performances significantly than TCPS and AGC alone.

## VII. Conclusion

A comprehensive mathematical model of an interconnected two area multiple units hydro–thermal system fitted with SSSC, TCPS in series with tie-line has been presented in this paper. The system frequency and tie-line power oscillations due to small load disturbances were found to persist for a longer duration even with optimal gain settings of integral controllers. Gain settings of integral controllers are also optimized by minimizing a quadratic performance index. Simulation results revealed that the frequencies and tie-power oscillations following sudden load disturbance in either of the areas were suppressed significantly using TCPS and SSSC and between two FACTS devices considered, SSSC have shown superiority over TCPS.

## Nomenclature

| | |
|---|---|
| F | Nominal system frequency |
| $T_P$ | Power system time constant |
| $K_P$ | Power system gain |
| $P_{rt}$ | Rated capacity of each control area |
| D | System damping of area |
| B | Frequency bias constant |
| $a_{12}$ | Control area capacity ratio |
| H | Inertia constant |
| $T_W$ | Nominal starting time of water in penstock |
| $T_{RS}$ | Hydro turbine speed governor reset time |
| $T_{RH}$ | Hydro turbine speed governor transient droop time constant |
| $T_{GH}$ | Hydro turbine speed governor main servo time constant |
| $T_G$ | Governor time constant of thermal area |
| $T_T$ | Steam turbine time constant |
| $K_R$ | Steam turbine reheat constant |
| $T_R$ | Steam turbine reheat time constant |
| apf | Area participation factor |

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## APPENDIX

### A: SYSTEM PARAMETERS

$K_{P1} = K_{P2} = K_P$ =120 Hz/p.u. MW
$T_{P1} = T_{P2} = T_P$ =20 s
$R_{HY} = R_{TH} = R$ =2.4 Hz/p.u. MW
$B_1 = B_2 = 0.4249$
$T_{SG}$ = 0.08 s
$T_T$ = 0.3 s
$T_{12}$ = 0.0866
$T_{GH}$ = 41.6 s
$T_{RH}$ = 0.513 s
$T_{RS}$ = 5 s
$K_R$=0.3
$T_R$=10 s
$T_W$ = 1 s
$D_1 = D_2$ = 8.333 x 10-3 p.u. MW/Hz
$P_{r1} = P_{r2}$ = 1200 MW

### B: SSSC PARAMETERS

$T_{SSSC}$=0.03 s
$K_{SSSC}$=0.297s
$T_1$=0.188
$T_2$=0.039
$T_3$=0.542
$T_4$=0.141

### C: TCPS PARAMETERS

$T_{PS}$=0.01s
$K_\phi$=1.5 rad/Hz
$\Phi_{max}=13^0$
$\Phi_{min} = -13^0$