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A SIMULATED ANNEALING BASED HYDROTHERMAL SYSTEM WITH THYRISTOR CONTROLLED PHASE SHIFTER UNDER OPEN MARKET SYSTEM

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ABSTRACT

This paper presents the analysis of Automatic Generation Control (AGC) of a two-area interconnected hydrothermal system with Thyristor Controlled Phase Shifter (TCPS) in series with the tie-line under open market system. It also involves the optimization of integral controller employing simulated annealing method. Open transmission access and the evolving of more socialized companies for generation, transmission and distribution affects the formulation of AGC problem. So the traditional AGC two-area system is modified to take into account the effect of bilateral contracts on the dynamics. It is possible to stabilize the system frequency and tie-power oscillations by controlling the phase angle of TCPS which is expected to provide a new ancillary service for the future power systems. A control strategy using TCPS is proposed to provide active control of system frequency. Gain settings of the integral controllers without and with TCPS are optimized using the Simulated annealing technique following a step load disturbance in either of the areas. Analysis reveals that a TCPS is quite capable of suppressing the frequency and tie-power oscillations effectively as compared to that obtained without TCPS

Keywords: hydrothermal, TCPS, simulated annealing, disco participation matrix, open market system.

I. INTRODUCTION

Large scale power systems are normally composed of control areas or regions representing coherent groups of generators. In a practically interconnected power system, the generation normally comprises of a mix of thermal, hydro, nuclear and gas power generation. However, owing to their high efficiency, nuclear plants are usually kept at base load close to their maximum output. Gas power generation is ideal for meeting the varying load demand. Thus the natural choice of AGC falls on either thermal or hydro units. A realistic situation may arise where an area regulated by hydro generation is interconnected to another area regulated by thermal generation. Nowadays worldwide, the electric power industry is in a transition from vertically integrated utility (VIU) scenario, where a single utility owned and operated the generation, transmission and distribution systems and provided power at regulated rates to the deregulated scenario, where, competitive companies sell unbundled power at lower rates. Furthermore, various kinds of apparatus with large capacity and fast power consumption such as testing plants for nuclear fusion, steel factories etc increase significantly. When these loads are concentrated in power systems, they may cause a serious problem of frequency oscillations. Therefore, it is very important to consider how the control services of system frequency should be implemented. In a deregulated environment, any power system control such as frequency, will serve as an ancillary service. Thus, stabilization of frequency oscillations in an interconnected power system becomes challenging when implemented in the future competitive environment. A new frequency stabilization service which emphasis not only efficiency, reliability and economics, but also, advanced and improved controls for satisfying the requirements of power system operation, is much in demand.

On the other hand, the concept of utilizing power electronic devices for power system control has been widely accepted in the form of Flexible AC Transmission Systems (FACTS) which provide more flexibility in power system operation and control [10]. This extra flexibility permits the independent adjustment of certain system variables such as power flows, which are not normally controllable. A Thyristor Controlled Phase Shifter (TCPS) is expected to be an effective apparatus for the tie-line power flow control of an interconnected power system In the analysis of an interconnected power system, some areas are considered as the channels of disturbances and in this situation, the conventional frequency control i.e., the governor may no longer be able to attenuate the large frequency oscillations due to its slow response [1, 11]. On the other hand, tie-line power flow control by a TCPS installed in series with the tie-line in between two areas of an interconnected power system has the possibility to control the system frequency positively. The proposed control strategy will be a new ancillary service for the stabilization of frequency oscillations of an interconnected power system. Literature survey shows ample applications of TCPS for the improvement of dynamic and transient stabilities of power systems [12]–[14]. However, no attempt has been made to improve the performance of AGC of interconnected power system under open market system considering TCPS in series with the tie-line. In the present work, analysis has been carried out for the AGC of

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interconnected hydrothermal power system under open market system considering a TCPS in series with the tie-line. An interconnected hydrothermal system involves widely different characteristics for the hydro and thermal subsystems. The characteristics of hydro turbines differ from steam turbines in that the relatively large water inertia used as a source of energy causes a considerably greater time lag in the response of the change in the prime mover torque to a change in gate position, and also an initial tendency for the torque to change in a direction opposite to that finally produced. The speed governor characteristics of the hydro units are widely different from that of the turbo governor. Moreover, the maximum permissible generation rate constraint for the hydro units is relatively much higher than the thermal units. Further, the effects of different Generation Rate Constraints (fairly slow response for the thermal plant and quite fast response for the hydro plant) on the selection of optimum controller settings for the thermal and hydro areas and on the system dynamic performance considering a TCPS in series with the tie-line is yet to be established. In view of the above, the main objectives of the present work are:

1) To study the effect of a Thyristor Controlled Phase Shifter (TCPS) in a tie-line on the AGC dynamics of a hydrothermal system
2) To develop a linearised model of a two area interconnected hydrothermal system under open market scenario considering a TCPS in series with the tie-line
3) To optimize the gain settings of the integral controllers with and without considering TCPS employing Simulated annealing method
4) To compare the dynamic responses with and without considering the TCPS.

II. TIE LINE POWER FLOW MODEL CONSIDERING TCPS

Under open market system the power system structure changed in such a way that would allow the evolving of more specialized industries for generation (Genco), transmission (Transco) and distribution (Disco). A detailed study on the control of generation in deregulated power systems is given in [15]. The concept of independent system operator (ISO) as an unbiased coordinator to balance reliability with economics has also emerged [16,17]. The assessment of Automatic Generation control in an open market environment is given in detail in [18,19] and also provides a detailed review over this issue and explains how an AGC system could be simulated after deregulation. The recent advances in power electronics have led to the development of the Flexible Alternating Current Transmission Systems (FACTS). FACTS devices are designed to overcome the limitations of the present mechanically controlled power systems and enhance power system stability by using reliable and high-speed electronic devices. One of the promising FACTS devices is the Thyristor Controlled Phase Shifter (TCPS). A TCPS is a device that changes the relative phase angle between the system voltages. Therefore, the real power flow can be regulated to mitigate the frequency oscillations and enhance power system stability. In this study, a two-area hydrothermal power system interconnected by a tie-line under open market scenario is considered.

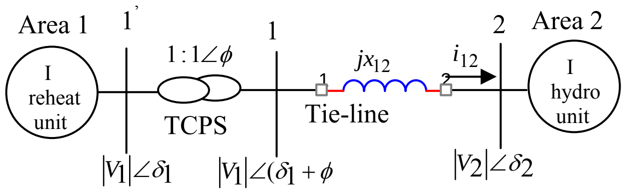

Figure-1. Interconnected hydrothermal two area system with TCPS in series with the Tie-line

Figure-1 shows the schematic of the two-area interconnected hydrothermal system considering a TCPS in series with the tie-line. TCPS is placed near area 1. Area 1 is the thermal area comprising of three reheat units and area 2 is the hydro area consisting of three hydro units. Without TCPS, the incremental tie-line power flow from area 1 to area 2 under open market system can be expressed as [1]

$$\Delta P^{o}_{tie12} = \frac{2\pi T^{o}_{12}}{s}(\Delta f_1 - \Delta f_2) \quad \text{.....(1)}$$

When a TCPS is placed in series with the tie line as in Fig 1, a current flowing from area 1 to area 2 can be written as

$$i_{12} = \frac{|V_1|\angle(\delta_1 + \phi) - |V_2|\angle\delta_2}{jX_{12}} \quad \text{.....(2)}$$

From Figure-1 it can also be written as

$$P_{tie12} - jQ_{tie12} = |V_1|\angle-(\delta_1 + \phi)\left(\frac{|V_1|\angle(\delta_1 + \phi) - |V_2|\angle\delta_2}{jX_{12}}\right) \quad \text{.....(3)}$$

Separating the real part of Eqn (3), we get

$$P_{tie12} = \frac{|V_1||V_2|}{X_{12}}\sin(\delta_1 - \delta_2 + \phi) \quad \text{.....(4)}$$

But in Eqn (4) moving δ_1, δ_2 and ϕ from their nominal values δ_1^o, δ_2^o and ϕ^o respectively, we get

$$\Delta P_{tie12} = \frac{|V_1||V_2|}{X_{12}}\cos(\delta_1^o - \delta_2^o + \phi^o)\sin(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) \quad \text{.....(5)}$$

But $(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi)$ is very small and hence, $\sin(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) \approx (\Delta\delta_1 - \Delta\delta_2 + \Delta\phi)$

So Eqn (5) can be written as

$$\Delta P_{tie12} = \frac{|V_1||V_2|}{X_{12}}\cos(\delta_1^o - \delta_2^o + \phi^o)(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) \quad \text{.....(6)}$$

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Let $T_{12} = \frac{|V_1||V_2|}{X_{12}}\cos(\delta_2^0 - \delta_2^0 + \varphi^0)$ …..(7)

Thus, Eqn.(6) reduces to $\Delta P_{tie12} = T_{12}(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi)$ …..(8)

Therefore, $\Delta P_{tie12} = T_{12}(\Delta\delta_1 - \Delta\delta_2) + T_{12}\Delta\varphi$ …..(9)

We also know that,

$\Delta\delta_1 = 2\pi\int \Delta f_1 dt$ and $\Delta\delta_2 = 2\pi\int \Delta f_2 dt$ …..(10)

From Eqns.(9) and (10), it can be written as

$\Delta P_{tie12} = 2\pi T_{12}(\int \Delta f_1 dt - \int \Delta f_2 dt) + T_{12}\Delta\varphi$ …..(11)

Taking the laplace transform of Eqn.(11), it can be written as

$$\Delta P_{tie12}(s) = \frac{2\pi T_{12}}{s}\left[\Delta F_1(s) - \Delta F_2(s)\right] + T_{12}\Delta\varphi(s) \quad .....(12)$$

As per Eqn.(12), it can be observed that the tie-line power flow can be controlled by controlling the phase shifter angle $\Delta\varphi$. The phase shifter angle $\Delta\varphi$ (s) can be represented as [12-14]:

$$\Delta\varphi(s) = \frac{K_\phi}{1 + sT_{ps}}\Delta Error_1(s) \quad .....(13)$$

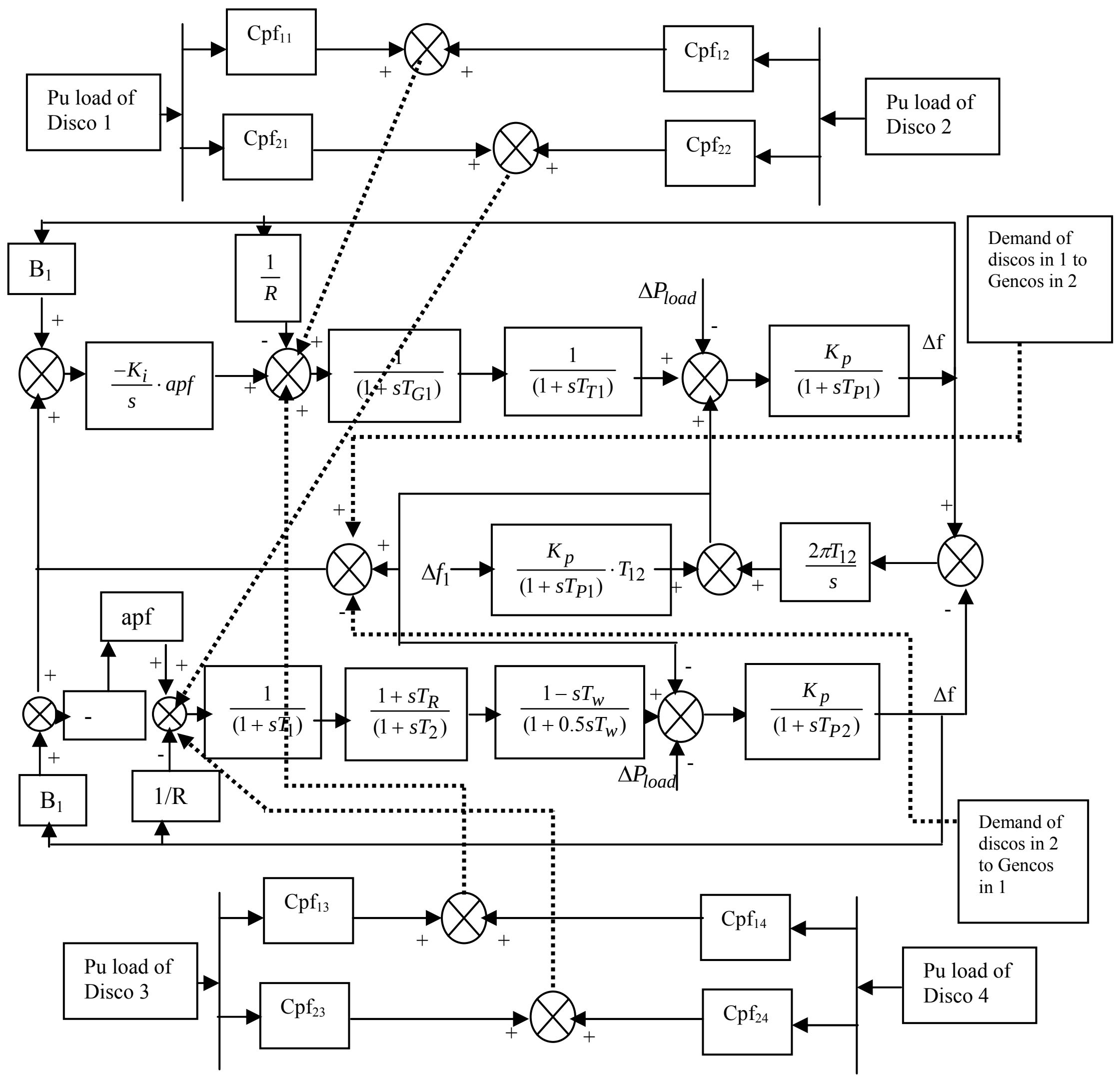

Figure-2. Two area hydrothermal system under open market scenario.

Where K_φ and T_{ps} are the gain and time constants of the TCPS. Thus, Eqn. (12) can be rewritten as

$$\Delta P_{tie12}(s) = \frac{2\pi T_{12}}{s}\left[\Delta F_1(s) - \Delta F_2(s)\right] + T_{12}\frac{K_\phi}{1 + sT_{ps}}\Delta Error_1(s) \quad .....(14)$$

If the frequency deviation Δf_1 is sensed, it can be used as the control signal (i.e., $\Delta Error_1 = \Delta f_1$) to the TCPS unit to control the TCPS phase shifter angle which in turn, controls the tie-line power flow. Thus,

$$\Delta\varphi(s) = \frac{K_\phi}{1 + sT_{ps}}\Delta F_1(s) \quad .....(15)$$

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and the tie-line power flow perturbation becomes

$$\Delta P_{tie12}(s) = \frac{2\pi T_{12}}{s}\left[\Delta F_1(s) - \Delta F_2(s)\right] + T_{12}\frac{K\varphi}{1+sT_{ps}}\Delta F_1(s) \quad .....(16)$$

But in the open market system the actual tie-line power flow also includes the demand from Discos in one area to Gencos in another area. It can be represented as follows.

$\Delta P_{tie\ 1\text{-}2,\ actual} = \Delta P_{tie12}(s)$ + (demand of Discos in area 2 from Gencos in area 1) – (demand of Discos in area 1 from Gencos in area2)

III. SYSTEM INVESTIGATION

The AGC system investigated is composed of an interconnection of two areas under open market system. Area 1 comprises of a reheat system and area 2 comprises of hydro system. 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 systems [20]. The detailed small perturbation transfer function block diagram model of two area hydrothermal system under open market scenario along with the incremental model of TCPS in series with the tie-line is shown in Figure 2. Nominal parameters of the TCPS system are given in the Appendix.

IV. OPTIMIZATION OF INTEGRAL GAIN SETTINGS

Simulated annealing method is used to obtain the optimum integral gain settings. A performance index which is denoted by $J = \int_0^t (\alpha \Delta f_1^2 + \beta \Delta f_2^2 + \Delta P_{tie12}^2)dt$ is minimized in the presence of GRCs to obtain the optimum values of K_{i1} and K_{i2}. A value of 0.65 is considered for both α and β. The simulated annealing method resembles the cooling process of molten metals through annealing. The algorithm for simulated annealing method can be written as shown below.

Step 1: Choose an initial point $x^{(0)}$, a termination criterion ε. Set T a sufficiently high value, number of iterations to be performed at a particular temperature n, and set t = 0.

Step 2: Calculate a neighbouring point $x^{(t+1)} = N(x^{(t)})$. Usually a random point in the neighborhood is created

Step 3: If $\Delta E = E(x^{(t+1)}) - E(x^{(t)}) < 0$, set t = t+1; else create a random number (r) in the range (0,1). If $r \le \exp(-\frac{\Delta E}{T}) set = t+1;$ else go to step 2

Step 4: If $\left|x^{(t+1)} - x^{(t)}\right| < \varepsilon$ and T is small, **Terminate**

else if (t mod n) = 0 then lower T according to a cooling schedule. And go to step 2. Else go to step 2.

Optimum values of integral gain settings of area 1 and area 2 without and with TCPS in series with the tie-line are tabulated in Table-1

Table-1. Optimum values of integral gain settings.

Area	Without TCPS	With TCPS in series with tie-line
Thermal	k_{i1} = 0.650	k_{i1} =0.940
Hydro	k_{i2} = 0.470	k_{i2} =0.570

From Table-1 it is seen that the optimum values of the integral gain settings in areas 1 and 2 considering TCPS are higher than those obtained without TCPS.

V. DYNAMIC RESPONSES AND DISCUSSIONS

Considering GRCs, simulation studies are performed to investigate the performance of the two-area hydrothermal system under open market system without and with TCPS in series with the tie-line. A step load disturbance of 0.04 pu MW is considered in either of the areas. Also an additional case is also considered when contract violation occurs in either area. So in this contact violation an additional load of 0.03 pu MW is considered in both the areas after the time span of 30 sec.

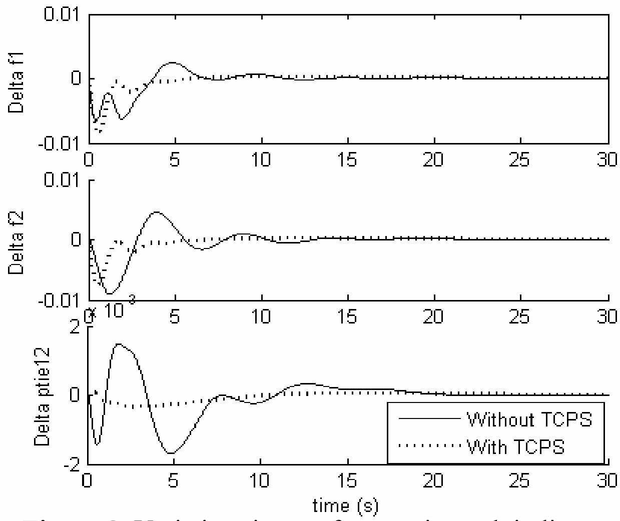

Figure-3. Variations in area frequencies and tie-line power deviations.

It is seen from Figure-3 that, with the TCPS in series with the tie-line, dynamic responses for Δf_1, Δf_2 have improved significantly and it can be observed that the oscillations in area frequencies have decreased to a considerable extent with the use of TCPS. Depicted in Figure-4 are the generations of Gencos in first area and Figure-5 depicts the generation of Gencos in second area for a load of 0.004 p.u Mw in both areas.

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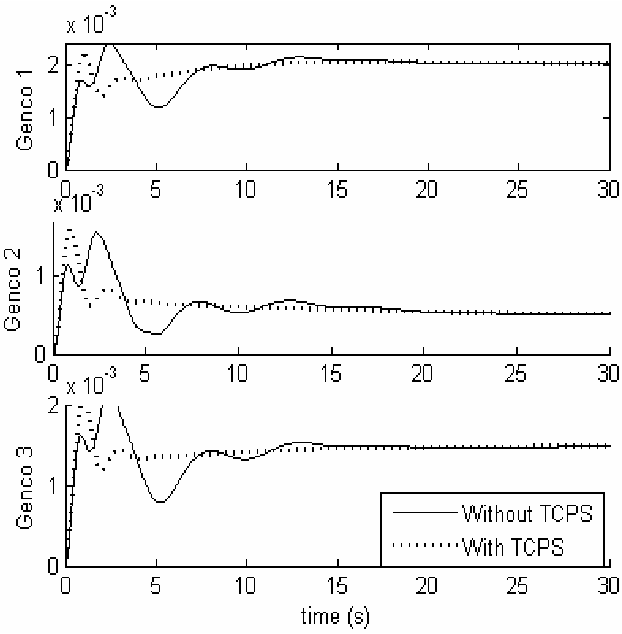

Figure-4. Generations of Gencos in area 1.

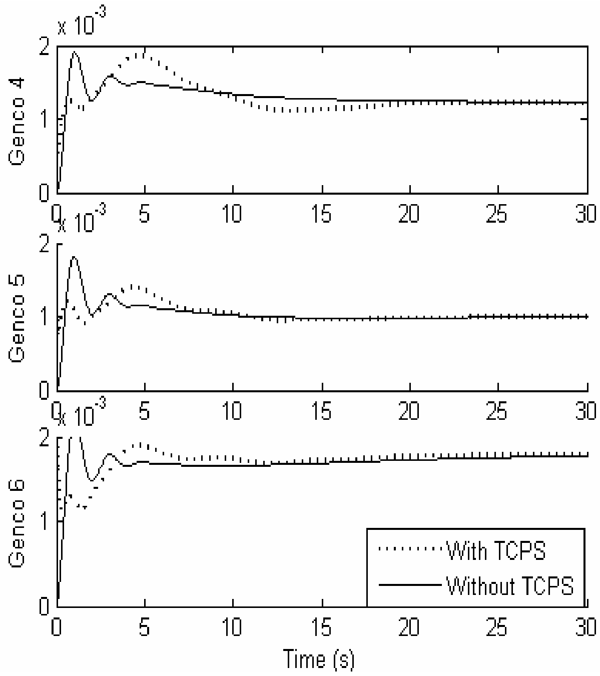

Figure-5. Generations of Gencos in area 2.

Figures 6-8 shown below show the case of contract violation where an additional load of 0.03 pu MW is demanded in each area. In this case, only the Gencos in that particular area where the load has occurred take up that extra load whereas the remaining ones generate the same amount of power which they had been generating before. This idea has been implemented in the block diagram and it has also been represented in block diagram of Figure-2.

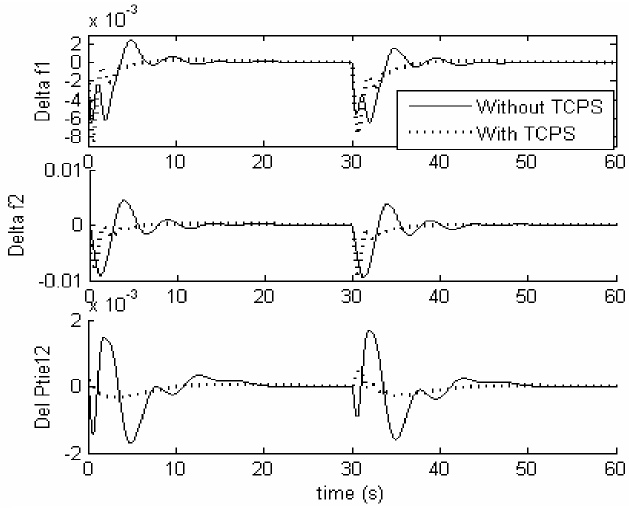

Figure-6. Variations in area frequencies and tie-line power deviations during contract violation.

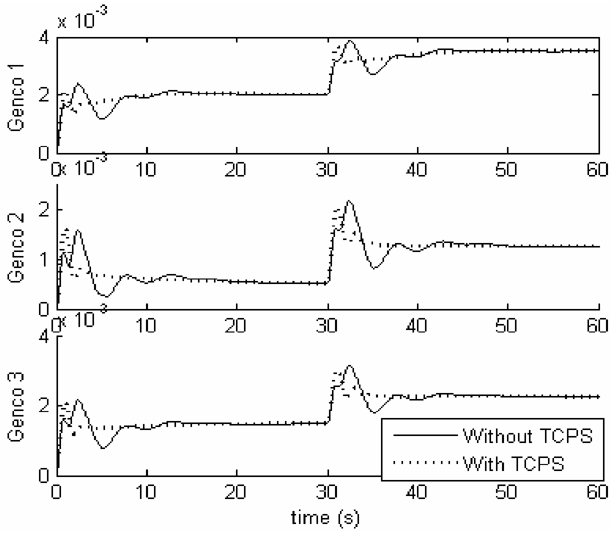

Figure-7. Generations of Gencos in area 1 during contract violation.

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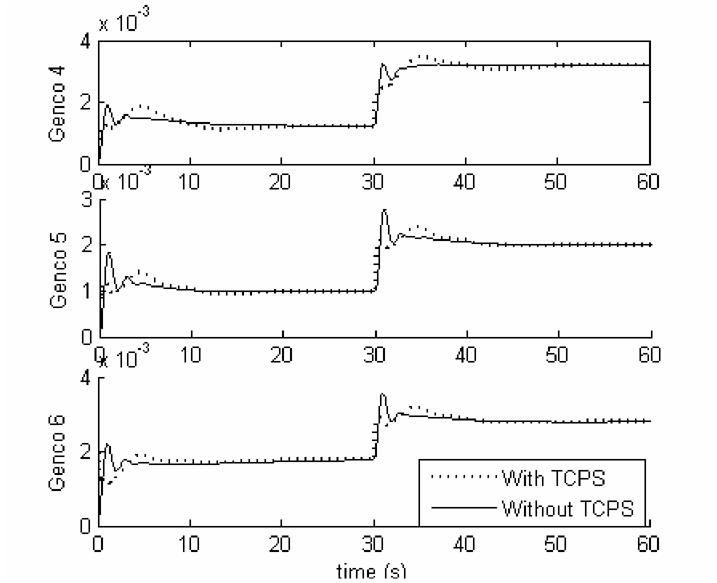

Figure-8. Generation of Gencos in area 2 during contract violation.

Depicted in Figure-9 are the frequency deviations for the various values of integral controllers generated during the process of simulated annealing. The optimum values of integral controllers without and with TCPS have already been tabulated in Table-1. Here also the oscillations in area frequencies have been greatly reduced by the use of TCPS.

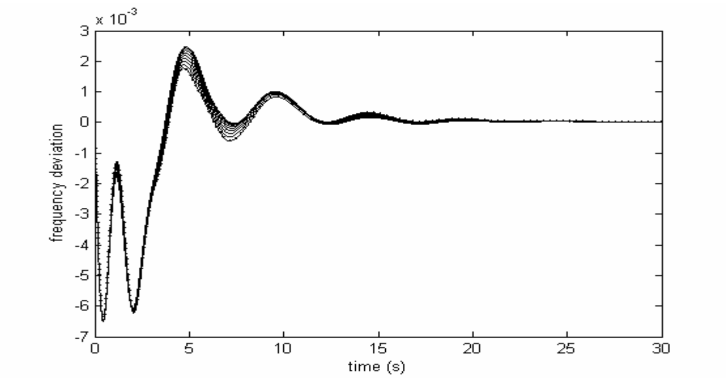

Figure-9. Variations in area frequencies during various values of integral controller.

VI. CONCLUSIONS

In this paper, a tie-line power flow control technique by TCPS has been proposed for a two-area interconnected hydrothermal power system under open market scenario. Gain settings of the integral controllers are optimized using Simulated Annealing technique in the presence of GRCs by minimizing a quadratic performance index. A control strategy has been proposed to control the TCPS phase angle which in turn controls the inter-area tie-line power flow. Simulation results reveal that frequencies and tie-power oscillations following sudden load disturbance in either of the areas can be suppressed by controlling the phase angle of TCPS. It may be therefore concluded that, the tie-line power flow control by a TCPS can be expected to be utilized as a new ancillary service for stabilization of frequencies and tie power oscillations in the deregulated environment of power systems.

VII. APPENDIX

All the notations carry the usual meanings

TCPS data:

$T_{PS} = 0.1s$

$K_{\phi} = 1.5 rad / Hz$

$\phi_{\max} = 10^{o}$

$\phi_{\min} = -10^{o}$

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