Effects of Thyristor Controlled Series Capacitor (TCSC) on Oscillations in Tie-Line Power and Area Frequencies in an Interconnected Non-Reheat Thermal Power System.

Nikhil M. Abraham
Executive Trainee
POWERGRID

Arun P Parameswaran
Research Scholar
NITK Suratkal

Rajesh Joseph Abraham
Asstt. Professor
IIST Trivandrum

Abstract: **This paper deals with automatic generation control of an interconnected thermal non-reheat power system in continuous mode by employing a Thyristor Controlled Series Capacitor (TCSC) in series with the line. Damping of the system frequency and tie-line power oscillations by controlling the reactance of the TCSC is presented. Gain values of the integral controllers are optimised using the integral squared error method by providing a step load disturbance in each of the areas by minimising a quadratic performance index. It is reported that TCSC can dampen the tie-line and power oscillations commendably under sudden load disturbances in any of the areas.**

Keywords— Automatic Generation Control (AGC), Inter Area Tie-line Power, TCSC Controller, Area Control Error, Integral Squared Error (ISE) technique.

1. Introduction:

A power system is considered to be a perfectly balanced one when the generation meets the load requirements. Under this criterion, the system parameters like the frequency, voltage and the power flow are at their nominal values. For large scale power systems comprising of a number of interconnected networks, the challenge is to keep the system frequency as well as the inter area tie power close to the nominal values as possible. For the same reason, Automatic Generation Control/Load Frequency Control (AGC/LFC) is important wherein the input mechanical power to the generators of each area is varied according to the load perturbations, resulting in a corresponding change in its speed and hence controlling the frequency of the output electrical power thereby maintaining the power exchange between the areas as scheduled.[1]. In the literature, considerable work has been devoted to AGC or LFC, of interconnected power systems. [2-7]. Elgerd and Fosha [2] have presented an analysis of AGC problem of a two-area non-reheat thermal system. Concordia and Kirchmayer [3] and Kirchmayer [4] have studied the AGC of a hydrothermal system considering non-reheat turbine and mechanical governor in hydro system, neglecting generation constraints. Jaleeli et al [5] have presented a detailed description of the functions and limitations of the Automatic Generation Control. Kothari et al [6] have developed a variable structure control strategy to automatic generation control of interconnected reheat thermal system. Chan et al [7] have reported a strategy for AGC of interconnected power systems using variable structure controllers. Literature survey for AGC shows that much of the attention has been given to designing various AGC controllers, whereas very less attention has been given to attenuating the oscillations in system frequency and tie-line power exchange. Though, attenuating the oscillations is not among the AGC objectives, it is necessary to control these oscillations arising from the load disturbances from any of the areas [8]. Thereby, these oscillations are minimised and are not allowed to interact with AGC at any cost [9]. High Voltage AC transmission systems incorporate power electronic based and other static controllers to enhance the controllability and the power transfer capability. These devices are termed as Flexible AC Transmission System (FACTS) Devices [11]. FACTS devices provide more flexibility in power system operation and control [10]. FACTS devices have fast controllability compared to the conventional devices. These devices are termed static due to absence of any moving parts like mechanical switches to perform the dynamic controllability. There are two different types of configurations available for the FACTS devices namely, Series Devices and Shunt devices respectively.

One of the major FACTS Series devices is Thyristor Controlled Series Capacitor (TCSC). TCSC is a capacitive reactance compensator which consists of a series capacitor shunted by the Thyristor Controlled Reactor (TCR). TCSC is primarily used for damping of the inter-area oscillations and thereby improving stability. It increases the damping when large electrical systems are interconnected and in addition, it can overcome the problem of SSR (Sub-Synchronous Oscillations). The control algorithm functions on the thyristor circuit in parallel to the main capacitor bank such that controlled charges are added to the main capacitor, making it a variable capacitor at fundamental frequency [12].

Literature survey shows that numerous amount of research has been done to study the dynamic behaviour of TCSC. Research on control strategies for TCSC can be traced back to 1966 when Kimbark[13] analysed the improvement in transient stability of power systems by using switched series capacitors. A lot of work has also been devoted to learn applications of TCSC for the improvement of dynamic and transient stabilities of power systems [13-18]. Rajaraman et al [14] have presented a method to compute the damping of sub-synchronous resonance modes with a TCSC. On the other hand, very less attention has been given to attenuating the oscillations in system frequency and tie-line power between the control areas after sudden load disturbances, by incorporating TCSC in series with the tie-line. The proposed control strategy will be very constructive in managing the frequency oscillations and tie-line oscillations within nominal values. Hence the prime incentive is to suppress the oscillations in system frequency and tie-line power exchange.

In this report, the authors propose to work with an interconnected non-reheat thermal power system with Generation Rate Constraints (GRCs) and studying the impact of utilising a FACTS controller like TCSC in damping each area's frequency oscillations and tie-line oscillations. Investigations are carried out to examine the capability of the TCSC damping controller in two-area interconnected power system. In view of the above, the main objectives of the present work are:

1. To implement a linearised model of a two-area interconnected non-reheat thermal system considering a TCSC in series with the tie-line.
2. To suppress the oscillations in the system frequency and tie-line power with the help of a TCSC connected in series with the tie-line of a two-area interconnected non-reheat thermal system.
3. To optimise the gain settings of the integral controllers without TCSC and after considering TCSC.
4. To judge the dynamic response with and without considering the TCSC.

2. Formulation of the problem by considering TCSC:

Flexible AC Transmission System (FACTS) devices are deployed in power systems to wield continuous control over the power flow patterns across the tie-line and frequency oscillations in both the areas. Thyristor Controlled Series Capacitor (TCSC) is a series FACTS device which allows rapid and continuous changes in the transmission line impedance. This is in order to provide smooth variation in the tie-line reactance. Since the reactance to the resistance ratio is quite high (X/R>= 10) the effect of the resistance in the dynamic performance investigation is neglected.

Without TCSC, the incremental tie-line power flow from area1 to area2 can be expressed as (1)

$$\delta P^{o}_{tie12} = 2\pi T^{o}_{12}(\delta f_1 - \delta f_2) \qquad (1)$$

where T^0_{12} is the synchronising coefficient and δf_1 and δf_2 are the frequency deviations in the areas 1 and 2 respectively. When a TCSC is placed in series with the tie-line as shown in the fig.1, the tie-line flow through the line becomes

$$P^0{}_{tie12} = \frac{|V_1||V_2|\sin(\alpha_1 - \alpha_2)}{X_{12} - X^0{}_c} \qquad (2)$$

where X^0_c is the impedance of the TCSC connected in series to the line. α_1, α_2 are the load angles of area 1 and area 2 respectively and X_{12} is the tie-line impedance.

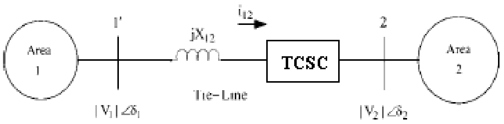

Figure 1: A simple diagram of a two area thermal system with TCSC.

Substituting $k^o_c = X^0_c/X_{12}$ in equation (2), we get

$$P^0_{tie12} = \frac{|V_1||V_2|\sin(\alpha_1 - \alpha_2)}{X_{12}(1 - k^0{}_c)} \qquad (3)$$

On perturbing k^o_c to k_c i.e from its nominal value, we get

$$P_{tie12} = \frac{|V_1||V_2|\sin(\alpha_1 - \alpha_2)}{X_{12}(1 - k_c)} \qquad (4)$$

Therefore the change in tie-line power flow as a result of perturbation is found out to be

$$\delta P_{tie12} = \frac{|V_1||V_2|\sin(\alpha_1-\alpha_2)}{X_{12}(1-k_c)} - \frac{|V_1||V_2|\sin(\alpha_1-\alpha_2)}{X_{12}(1-k^0{}_c)} \quad (5)$$

$$\delta P_{tie12} = \frac{|V_1||V_2|\sin(\alpha_1-\alpha_2)((\delta k_c)}{X_{12}(1-k_c+k_c^0 k_c-k_c^0)} \quad (6)$$

where δk_c is the change in percentage compensation of impedance of the TCSC. The nominal value of k_c is 0.5 i.e k^o_c= 0.5. Without loss of generality $k_c.k^o_c$ can be assumed to be negligible, as both being less than 1 and hence substituting the value of k^o_c in equation (6), we can further simplify the given equation to:

$$\delta P_{tie12} = \frac{2|V_1||V_2|\sin(\alpha_1-\alpha_2)(\delta k_c)}{X_{12}(0.5-\delta k_c)} \quad (7)$$

Since, δk_c must lie between -0.4 and 0.3. [9]

i.e $-0.4 \leq \delta k_c \leq 0.3$;

Thus the mean value of $(0.5-\delta k_c)$ is calculated to be $\frac{0.9+0.2}{2} = 0.55 = 0.5$(approx.)

So the change in the tie-line power is reported to be

$$\delta P_{tie12} = \frac{4|V_1||V_2|\sin(\alpha_1-\alpha_2)(\delta k_c)}{X_{12}} \quad (8)$$

3.Providing a control strategy to TCSC controller:

As per (8), the tie line power oscillations can be damped by governing the change in percentage compensation of impedance of the TCSC. We present a signal named δError(s) as the control signal to the TCSC damping controller.

$$\delta k_c(s) = \frac{\delta Error(s)}{(1+sT_{TCSC})}$$

where T_{TCSC} is the time constant of the TCSC block and δError(s) is the control signal which controls δk_c.. δError(s) can be any signal such as frequency deviation δf1, area control error (ACE) etc. Here we present the error signal to be $ACE_1(s)$ i.e. δError(s) = $ACE_1(s)$.

$$\delta k_c(s) = \frac{\delta ACE1(s)}{(1+sT_{TCSC})} \quad (9)$$

Hence the tie-line power disturbance becomes

$$\delta P_{tie12} = \frac{4|V_1||V_2|\sin(\alpha_1-\alpha_2)(\delta ACE1(s))}{X_{12}(1+sT_{TCSC})} \quad (10)$$

Substituting $\delta ACE1(s) = \delta P_{tie12}(s) + B_1\delta f_1(s)$ in (10) we get,

$$\delta P_{tie12} = \frac{4|V_1||V_2|\sin(\alpha_1-\alpha_2)(\delta P_{tie12}(s)+B_1\delta f_1(s))}{X_{12}(1+sT_{TCSC})} \quad (11)$$

4. System Investigated:

A large power system consists of a number of control areas interconnected by tie-lines. There are different complicated non-linear models for large scale power systems. However for the design of AGC, a simplified and linear model is generally used[19]. The system considered for study is a two-area system, with two non-reheat power system units in each area, connected by a single tie-line. The TCSC (Thyristor controlled series capacitor) is connected in series with the tie-line. GRCs have also been considered with 15% for raising and lowering generations for area 1 and 5% for raising and lowering generations for area 2 respectively. GRCs have been considered to incorporate the rapid power increase, which could draw out steam from the boiler system only to cause steam condensation due to adiabatic expansion. Hence when generation power reaches this marginal upper bound, GRC restricts the further increase in the power of the turbine.

The detailed transfer function models of speed governors and turbines present are developed in the IEEE Committee Report on Dynamic Models for Steam and Hydro turbines in Power System Studies [23].

A load perturbation of 1% p.u has been provided in both the areas respectively. A block diagram model, with detailed transfer function, for a two area non-reheat power system with two generating units each, is shown in Figure 2.

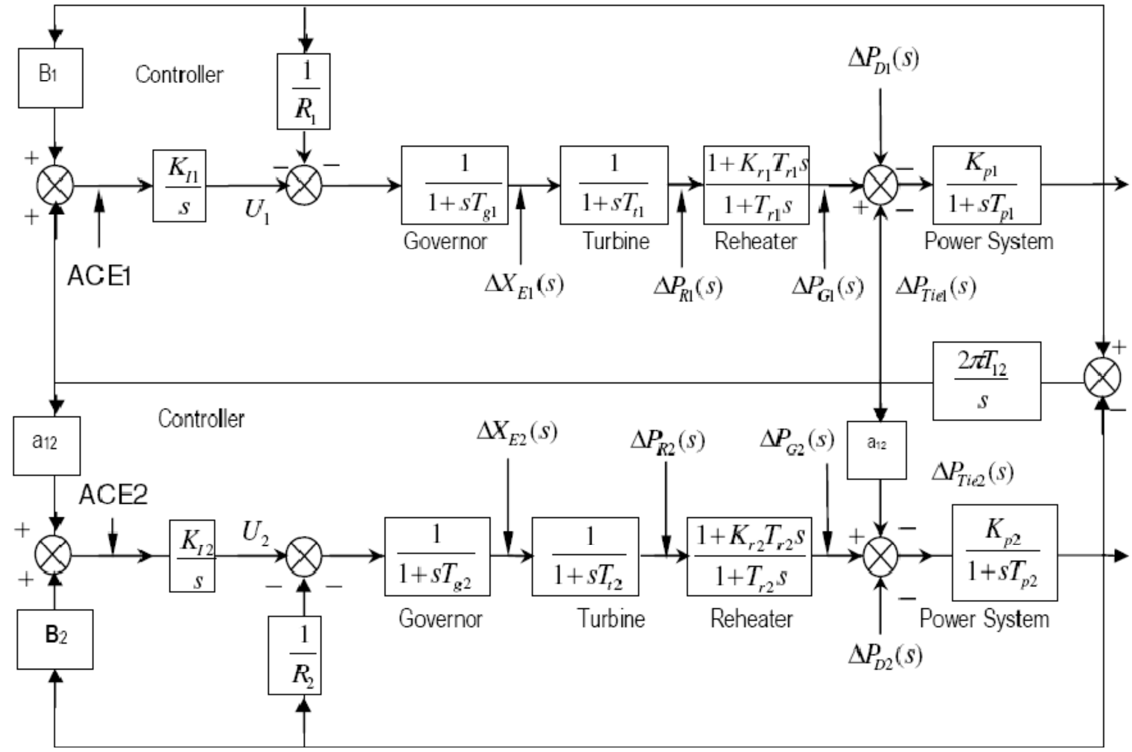

Figure 2 : A SIMULINK block diagram representation of a two area non reheat thermal power system.

5. State Space Representation:

The power system model considered is a linear continuous time dynamic system. Hence it can be represented by the standard state space model as

X’ = AX+BU+µp ; where X, U and p are the state, control and the disturbance vectors, respectively, and A, B and µ are state matrices associated with them.

For the system considered,

X’ = AX+BU+µp

$$X = \begin{bmatrix} \Delta f_1, \Delta f_2, \Delta P_{tie12}, \Delta P_{t1}, \Delta P_{t2}, \Delta P_{g1}, \Delta P_{g2}, \Delta P_{g3} \\ \Delta P_{g4}, \Delta P_{r1}, \Delta P_{r2}, \Delta P_{r3}, \Delta P_{r4}, \Delta k_{TCSC} \end{bmatrix}^T$$

$$U = [U_1 U_2]^T \quad \text{and} \quad p = [\Delta P_{d1} \Delta P_{d2}]^T$$

6. Optimisation of integral gain settings:

The optimisation of the integral controllers of the PID controllers is performed by using the ISE technique, since trial and error method of the gains by indirect methods does not seem to be appropriate. The performance index chosen for minimisation of the gains in the PID controller is

$KJ = \int_0^T (w_1 f_1^2 + w_2 f_2^2 + w_3 f_3^2)\, dt$

It is minimised for 0.01p.u of step-load disturbance in either of the areas in the presence of GRCs. The Gain value corresponding to the minimum performance index (KJ) is taken as the optimised value.

Without loss of generality, the weight constants (w_1,w_2,w_3) are each considered to be equal to be one. The controller settings of either thermal systems are optimised by considering the other area as uncontrolled as presented. Optimum values of the gain settings before and after installing the TCSC has been tabulated in Table 1.

Table I

Percentage of load sharing by each area	Step load disturbance	Optimum gain integral settings for thermal area 1 without TCSC	Optimum gain integral settings for thermal area 1 with TCSC	Optimum gain integral settings for thermal area 2 without TCSC	Optimum gain integral settings for thermal area 2 with TCSC
Area 1 = 50% Area 2 =50%	0.01 p.u	$Ki_1 = 0.0630$	$Ki_1 = 0.0380$	$Ki_2 = 0.0360$	$Ki_2 = 0.0120$

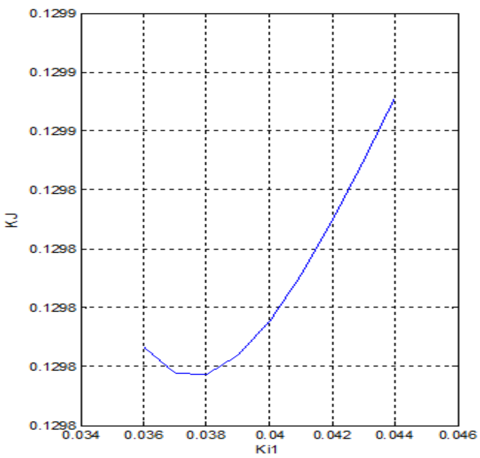

Figure 3: Plot between KJ and Ki_1 (with TCSC)

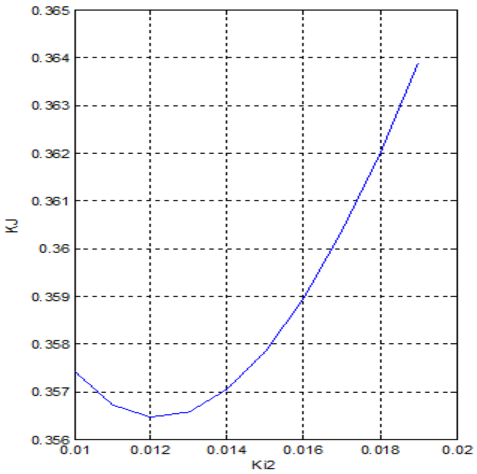

Figure 4: Plot between KJ and Ki_2 (with TCSC)

7. Simulation results and Discussions:

The responses of the two area non-reheat thermal power system have been studied in detail. Fig 5-7 shows the dynamic responses for frequency and tie-line power deviations and Fig.8-11 shows the generation responses of all the four generating units for 1% step load disturbance in area 1 considering apf1=apf2=apf3=apf4=0.5. The responses have been simulated for both conditions i.e. without considering TCSC units and with TCSC units respectively. From Figs.5-11, it is evident that the dynamic responses have improved significantly with the use of TCSC units. As the load disturbance has occurred in area 1, at steady state, the power generated by the generating units in area 1 are in proportion to the ACE participation factors.

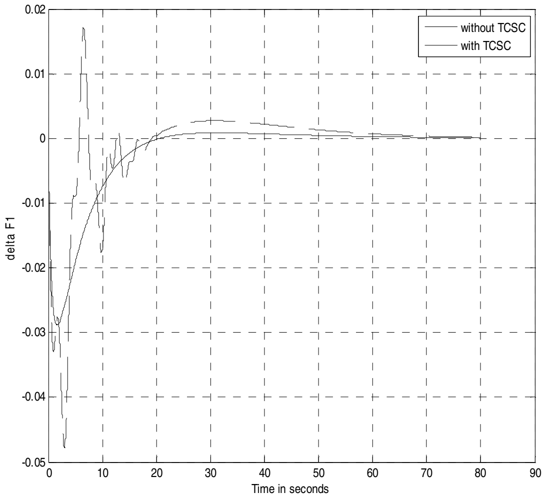

Figure 5: Plots depicting the frequency damping in Area 1 for both conditions i) without TCSC ii) with TCSC.

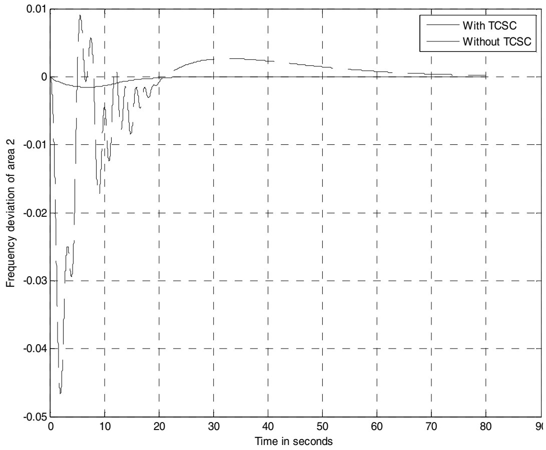

Figure 6: Plots depicting the frequency damping in Area 2 for i) without TCSC ii) with TCSC.

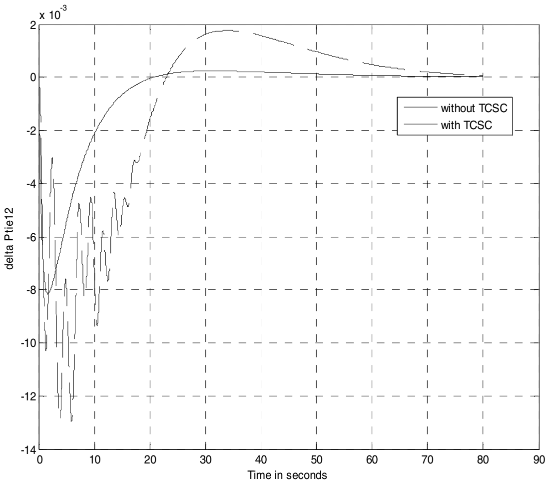

Figure 7: Plots depicting the damping of oscillations of tie-line power for i) without TCSC ii) with TCSC.

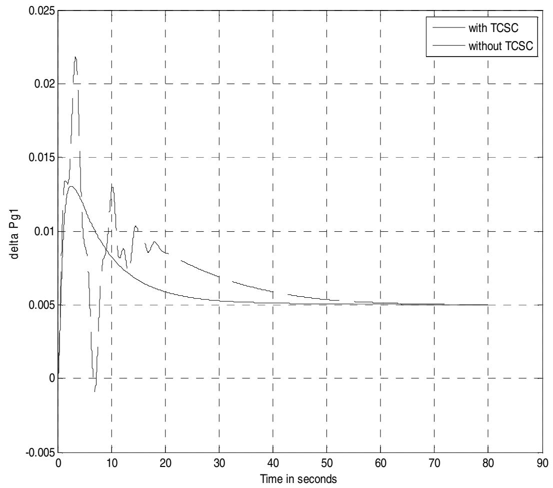

Figure 8: Plots depicting the generation response at generating unit 1 in Area 1 for i) without TCSC ii) with TCSC.

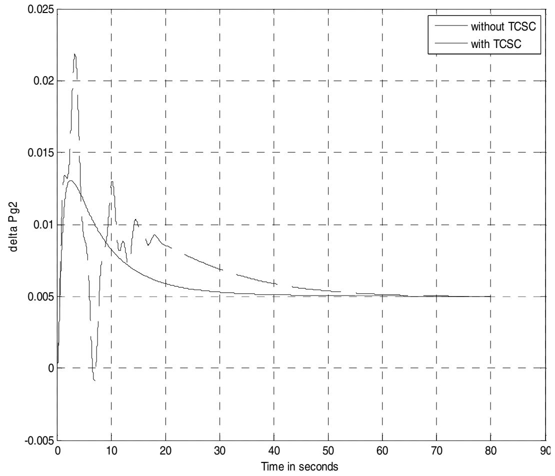

Figure 9: Plots depicting the generation response at generating unit 2 in Area 1 for both conditions i) without TCSC ii) with TCSC.

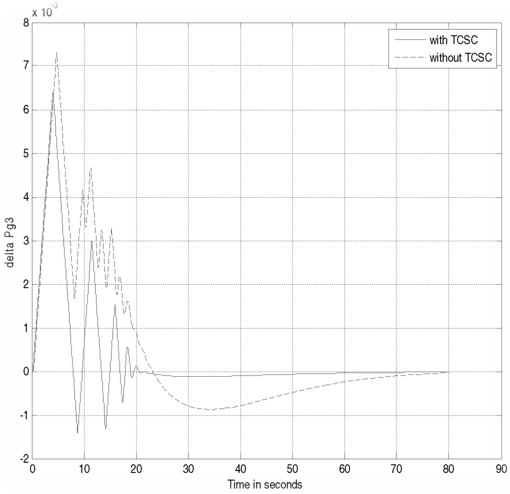

Figure 10: Plots depicting the generation response at generating unit 1 in Area 2 for i) without TCSC ii) with TCSC.

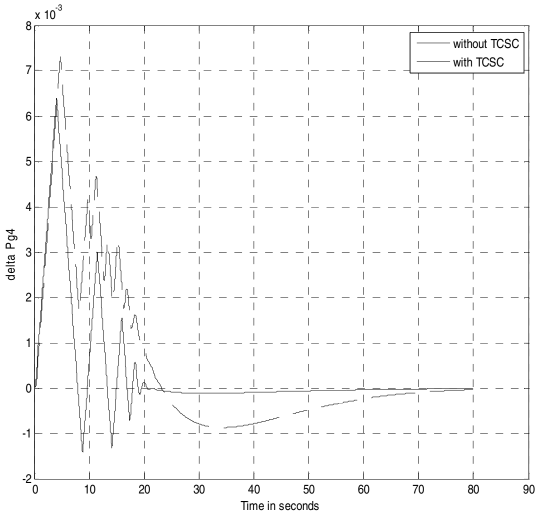

Figure 11: Plots depicting the generation response at generating unit 2 in Area 2 for i) without TCSC ii) with TCSC.

8. Conclusion:

In this paper, a new tie line power flow control technique by TCSC has been proposed for a two area interconnected non-reheat thermal power system. Gain settings of the integral controllers for both conditions i.e., without and with TCSC in series with the tie-line, are optimised using the ISE method, also taking into consideration, the GRCs. The motivation of using this technique is because of the complexity of the actual uncertainty of multivariable operating conditions. Subsequently a control strategy has been proposed to control the TCSC reactance, which in turns controls the inter–area tie-line power flow. As established above, the TCSC, when present in series with the tie-line influences the tie-line impedance from the ACE, which in turn will suppress the oscillations in the area frequencies and tie-power following sudden load disturbances. It may be concluded that a TCSC can be successfully installed in series with the tie-line for controlling the tie-line power flow for all load changes.

9. Acknowledgement:

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10. References:

1. Kundur,P.:”Power System Stability and Control”,Tata McGraw Hill,2009.
2. Elgerd O.I. and Fosha,C.:”Optimum megawatt frequency control of multi-area electric energy systems”,IEEE Trans.

Power Appar. Syst.,1970,89,(4),pp.556-563.

3. Concordia,C. and Kirchmayer,K.L:"Tie-line power and frequency control of electric power systems:Part II,"AISE trans,III-A,vol.73,pp.133-146,Apr.1954.
4. Kirchmayer,L.K:"Economic Control of Interconnected Systems".New York:Wiley,1959.
5. Jaleeli,Nasser and VanSlyck,L.S:"Understanding Automatic Generation Control",IEEE Trans on Power Systems,Vol.7,No.3,Aug1992.
6. Das,D.,Kothari,M.L,Kothari,D.P and Nanda,J.:" Variable structure control strategy of interconnected reheat system.".IEE Proc.-D.Vol.138,No.6,Nov.1991.
7. Chan,Wah-Chun and Hsu,Y.Y:"Automatic Generation Control of Interconnected power systems using variable structure controllers".IEE proc.,Vol.128,Pt.C,No.5,Sept.1981.
8. Pal,B.C, Coonick,A.H, and Macdonald,D.C:"Robust damping controller design in power systems with superconducting magnetic energy storage devices",IEEE trans. Power Syst.,2000,15,(1),pp.320-325.
9. R.J. Abraham, D.Das and A.Patra:" Effect of TCPS on oscillations in tie-power and area frequencies in an interconnected hydrothermal power system."IET Gener.Transm.Distrib.,2007,1,(4),pp.632-639.
10. Pal,B.C, and Chaudhari,B.:"Robust control in power systems'(Springer,2005)
11. Hingorani,N.G and Gyugi,L.:"Understanding FACTS" (IEEE Press,2000)
12. Pal,B.C, Rehantz,C. and Zhang, X.P:"Flexible AC Transmission Systems: Modelling and Control",(Springer,2006)
13. Kimbark, E.W:"Improvement of System stability by switched series capacitors",IEEE Trans. Power Apparatus Syst. 1966,PAS-85,(2),pp.180-188
14. Rajaraman et al, Computing the damping of sub-synchronous oscillations due to a TCSC, IEEE Trans on Power Del,Vol.11,No.2,April 1996.
15. Jonas Persson, Lennart Soder:"Validity of a linear Model of a thyristor controlled series capacitor for Dynamic Simulations", in Proc.14th Power Systems Computation Conference, June 24th - 28th,2002,Sevilla,Spain..
16. P. Mattavelli,G.C Verghese,A.M Stankovic,"Phasor dynamics of Thyristor Controlled Series Capacitor Systems",IEEE Summer Meeting 532-2 PWRS,1996.
17. H.A.Othman, L.Angquist, et al.,:"Analytical Modeling of Thyristor-Controlled Series Capacitors for SSR studies",IEEE Trans. Power Systems,Vol.11,No.1,1996,pp.119-127.
18. John J Paserba,Nicholas W.Miller et al,"A thyristor Controlled Series Compensation Model for Power System Stability Analysis",IEEE Trans.Power Delivery,Vol.10,No.3,1995,pp.1471-1478.
19. Saadat,H.:"Power System Analysis", McGraw Hill,USA,1999.
20. Ibraheem, Prabhat Kumar and D. P. Kothari "Recent Philosophies of Automatic Generation Control Strategies in Power Systems", IEEE Trans. on Power System, Vol. 20, No.1, pp. 346-357, Feb 2005.
21. K. C. Divya and P. S. N. Rao, "A Simulation Model for AGC Studies of Hydro-Hydro Systems" Electrical Power and Energy Systems 27, pp.335-342, 2005
22. R.J. Abraham, D.Das and A.Patra: "AGC study of a Hydrothermal system with SMES and TCPS", European Transactions on Elecrical Power, Vol.19, pp.487-498, April 2009.
23. IEEE Committee Report: 'Dynamic models for steam and hydro turbines in power system studies', IEEE Trans. Power Appar. Syst., 1973, 92, (6), pp. 1904–1915.
24. N. Cohn, Control of Generation and Power Flow on Interconnected Systems, New York, John Wiley,1986.