Asian Journal of Electrical Sciences
ISSN: 2249-6297 (P) Vol.6 No.2, 2017, pp.37-50

DOI: https://doi.org/10.51983/ajes-2017.6.2.1997

Performance Analysis of Different Tie-Line for Synchronization of 12-Area Two Interconnected Thermal Power Grid

Pankaj Kumar Sahu
Chhattisgarh Swami Vivekanand Technical University (CSVTU),
Bhilai, Chhattisgarh, India
E-Mail: pankajiiscb@gmail.com

(Received 2 September 2017; Revised 25 September 2017; Accepted 26 October 2017; Available online 3 November 2017)

***Abstract* - This paper represents the advantages of HVAC-HVDC parallel tie-line as compare to the Flexible AC Transmission System (FACTS) tie-line and normal HVAC tie-line for synchronization of 12-area two interconnected thermal power grid with its all 12 areas when load changed in power grid-1 (area-6). After load change in power grid-1 (area-6), 12-area two interconnected thermal power grid with its all 12 areas are synchronized at the same time only in case of HVAC-HVDC parallel tie-line. This paper also shows the Flexible AC Transmission System (FACTS) tie-line is better as compare to the normal HVAC tie-line. Performance analysis of different tie-line for synchronization or load (machine) frequency control of 12-area two interconnected thermal power grid is done in terms of settling time of frequency deviation of all 12 areas and settling time of tie-line power deviation of two interconnected areas or two interconnected power grid by using conventional integral controller when load changed in power grid-1 (area-6).**
***Keywords*: 12-Area Two Interconnected Thermal Power Grid, Synchronization or LFC- Load Frequency Control, HVAC tie-line: High Voltage Alternating Current tie-line, FACTS tie-line: Flexible AC Transmission System tie line, HVAC-HVDC parallel tie-line: High Voltage Alternating Current - High Voltage Direct Current parallel tie-line, TCPS-Thyristor Control Phase Shifter, Conventional Integral Controller**

I. INTRODUCTION

For clear representation of performance analysis of different tie-line for synchronization of 12-area two interconnected thermal power grid, this research work is done with 12-area two interconnected thermal power grid as a traditional power grid system accepted reheater any nonlinear element like governor dead band, boiler dynamics generation rate constraint, zero crossing and time delay elements are not considered and conventional integral controller is used for synchronization or load (machine) frequency control of 12-area two interconnected thermal power grid system.

In 12-area two interconnected thermal power grid system, each power grid consist 6 areas (6 thermal power stations), so that total numbers of areas (power stations) in two interconnected thermal power grid is 12.

Power Grid-1 (Area-6): The area-6 is also called power grid-1 and power grid-1 is receiving power from its interconnected separate areas (area-1, area-2, area-3, area-4, area-5) & sending power for power grid-2.

Power Grid-2 (Area-12): The area-12 is also called power grid-2 and power grid-2 is receiving power from power grid-1 and its interconnected separate areas (area-7, area-8, area-9, area-10, area-11).

The three types of tie-line are applied for interconnection of individual areas to the each power grids and interconnection of two power grids.

1. Normal HVAC Tie-Line.
2. HVAC-HVDC Parallel Tie-Line.
3. Flexible AC Transmission System (FACTS) Tie-Line.
   Load change in power grid-1: ΔP_{L6} = 0.01p.u.

II. MATHEMATICAL MODEL OF TIE-LINE POWER EXCHANGE

A. 12-Area Two Interconnected Thermal Power Grid with Normal HVAC and HVAC-HVDC parallel Tie-Line

The 12-Area Two Interconnected Thermal Power Grid with Normal HVAC Tie-Line as shown in figure 1.

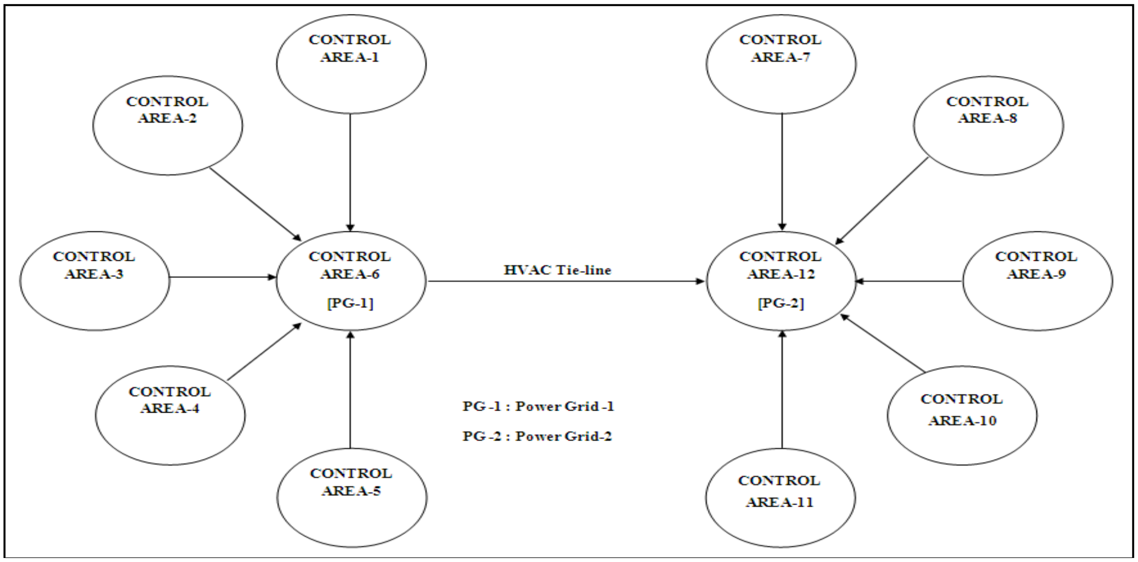

Fig.1 12-Area two interconnected thermal power grid with HVAC tie-line.

The power transfer from power grid-1 to power grid-2, then the tie-line power equation is

$$P_{Tie612} = \frac{|V_6||V_{12}|}{X_{612}} \sin(\delta_6 - \delta_{12})$$

Where δ_6, δ_{12} = End voltage power angle of two equivalent power system (load).

The incremental tie-line power equation in p.u. is

$$\Delta P_{Tie612} = T_{612} (\Delta\delta_6 - \Delta\delta_{12})$$

Where $\Delta\delta_6$, $\Delta\delta_{12}$ = incremental change in power angle of two generator and T_{612} is Synchronizing coefficient

$$T_{612} = \frac{|V_6||V_{12}|}{P_{r6}\, X_{612}} \cos(\delta_6 - \delta_{12})$$

Also the power angle $\Delta\delta_6$ & $\Delta\delta_{12}$ are the integral of incremental frequencies, then

$$\Delta\delta_6 = 2\pi\int_0^t \Delta F_6 dt \ \& \ \Delta\delta_{12} = 2\pi\int_0^t \Delta F_{12}\, dt$$

So that, $\Delta P_{Tie612} = 2\pi T_{612} \left(\int_0^t \Delta F_6\, dt - \int_0^t \Delta F_{12}\, dt\right)$

Similarly the power transfer from power grid-2 to power grid-1 then tie-line power equation is

$$\Delta P_{Tie126} = 2\pi T_{126} \left(\int_0^t \Delta F_{12}\, dt - \int_0^t \Delta F_6\, dt\right)$$

Where T_{126} = Synchronizing coefficient

$$T_{126} = \frac{|V_{12}||V_6|}{P_{r12}\, X_{126}} \cos(\delta_{12} - \delta_6)$$

Also the incremental power in p.u. is

$T_{126} = \frac{-P_{r6}}{P_{r12}} T_{612}$ & Area capacity ratio $a_{612} = \frac{-P_{r6}}{P_{r12}}$

If both areas capacities are equal and losses are neglected are ($P_{r6} = P_{r12}$), then

$\Delta P_{Tie126} = a_{612} \Delta P_{Tie612} = -\Delta P_{Tie612}$ so on.

The power transfer from area-1 to area-6 (power grid-1), then the tie-line power equation is $\Delta P_{Tie1}(s)$

$$= \Delta P_{Tie16}(s) = \frac{2\pi\, T_{16}}{s} [\Delta F_1(s) - \Delta F_6(s)]$$

The power transfer from area-2 to area-6 (power grid-1), then the tie-line power equation is $\Delta P_{Tie2}(s)$

$$= \Delta P_{Tie26}(s) = \frac{2\pi\, T_{26}}{s} [\Delta F_2(s) - \Delta F_6(s)]$$

The power transfer from area-3 to area-6 (power grid-1), then the tie-line power equation is $\Delta P_{Tie3}(s)$

$$= \Delta P_{Tie36}(s) = \frac{2\pi\, T_{36}}{s} [\Delta F_3(s) - \Delta F_6(s)]$$

The power transfer from area-4 to area-6 (power grid-1), then the tie-line power equation is $\Delta P_{Tie4}(s)$

$$= \Delta P_{Tie46}(s) = \frac{2\pi\, T_{46}}{s} [\Delta F_4(s) - \Delta F_6(s)]$$

The power transfer from area-5 to area-6 (power grid-1), then the tie-line power equation is $\Delta P_{Tie5}(s)$

$$= \Delta P_{Tie56}(s) = \frac{2\pi\, T_{56}}{s}\,[\Delta F_5(s) - \Delta F_6(s)]$$

The power transfer from area-7 to area-12 (power grid-2), then the tie-line power equation is

$$\Delta P_{Tie7}(s) = \Delta P_{Tie712}(s) = \frac{2\pi\, T_{712}}{s}\,[\Delta F_7(s) - \Delta F_{12}(s)]$$

The power transfer from area-8 to area-12 (power grid-2), then the tie-line power equation is

$$\Delta P_{Tie8}(s) = \Delta P_{Tie812}(s) = \frac{2\pi\, T_{812}}{s}\,[\Delta F_8(s) - \Delta F_{12}(s)]$$

The power transfer from area-9 to area-12 (power grid-2), then the tie-line power equation is

$$\Delta P_{Tie9}(s) = \Delta P_{Tie912}(s) = \frac{2\pi\, T_{912}}{s}\,[\Delta F_9(s) - \Delta F_{12}(s)]$$

The power transfer from area-10 to area-12 (power grid-2), then the tie-line power equation is

$$\Delta P_{Tie10}(s) = \Delta P_{Tie1012}(s) = \frac{2\pi\, T_{1012}}{s}\,[\Delta F_{10}(s) - \Delta F_{12}(s)]$$

The power transfer from area-11 to area-12 (power grid-2), then the tie-line power equation is

$$\Delta P_{Tie11}(s) = \Delta P_{Tie1112}(s) = \frac{2\pi\, T_{1112}}{s}\,[\Delta F_{11}(s) - \Delta F_{12}(s)]$$

The tie-line power equation of power grid-1 (control area-6) is $\Delta P_{Tie6}(s)$, then

$$\Delta P_{Tie6}(s) = a_{16}\,\Delta P_{Tie1}(s) + a_{26}\,\Delta P_{Tie2}(s) + a_{36}\,\Delta P_{Tie3}(s) + a_{46}\,\Delta P_{Tie4}(s) + a_{56}\,\Delta P_{Tie5}(s) + \Delta P_{Tie612}(s)$$

$$[\text{Here } \Delta P_{Tie612}(s) \neq \Delta P_{Tie6}(s)]$$

$$= a_{16}\,\Delta P_{Tie16}(s) + a_{26}\,\Delta P_{Tie26}(s) + a_{36}\,\Delta P_{Tie36}(s) + a_{46}\,\Delta P_{Tie46}(s) + a_{56}\,\Delta P_{Tie56}(s) + \Delta P_{Tie612}(s)$$

$$= \frac{2\pi}{s}\,[\sum_{i=1,2,3,4,5} a_{i6} T_{i6}\,\Delta F_i(s) - \sum_{i=1,2,3,4,5} a_{i6} T_{i6}\,\Delta F_6(s)\,] + \Delta P_{Tie612}(s)$$

$$= \frac{2\pi\, a_{16} T_{16}}{s}\,[\Delta F_1(s) - \Delta F_6(s)] + \frac{2\pi\, a_{26} T_{26}}{s}\,[\Delta F_2(s) - \Delta F_6(s)] + \frac{2\pi\, a_{36} T_{36}}{s}\,[\Delta F_3(s) - \Delta F_6(s)] \quad (1)$$

$$+ \frac{2\pi\, a_{46} T_{46}}{s}\,[\Delta F_4(s) - \Delta F_6(s)] + \frac{2\pi\, a_{56} T_{56}}{s}\,[\Delta F_5(s) - \Delta F_6(s)] + \frac{2\pi\, T_{612}}{s}\,[\Delta F_6(s) - \Delta F_{12}(s)] \quad (1)$$

The tie-line power equation of power grid-2 (control area-12) is $\Delta P_{Tie12}(s)$, then

$$\Delta P_{Tie12}(s) = a_{612}\,\Delta P_{Tie612}(s) + a_{712}\,\Delta P_{Tie7}(s) + a_{812}\,\Delta P_{Tie8}(s) + a_{912}\,\Delta P_{Tie9}(s) + a_{1012}\,\Delta P_{Tie10}(s) + a_{1112}\,\Delta P_{Tie11}(s)$$

$$[\text{Here } \Delta P_{Tie612}(s) \neq \Delta P_{Tie6}(s)]$$

$$= a_{612}\,\Delta P_{Tie612}(s) + a_{712}\,\Delta P_{Tie712}(s) + a_{812}\,\Delta P_{Tie812}(s) + a_{912}\,\Delta P_{Tie912}(s) + a_{1012}\,\Delta P_{Tie1012}(s) + a_{1112}\,\Delta P_{Tie1112}(s)$$

$$= \frac{2\pi}{s}\,[\sum_{k=6,7,8,9,10,11} a_{k12}\, T_{k12}\,\Delta F_k(s) - \sum_{k=6,7,8,9,10,11} a_{k12}\, T_{k12}\,\Delta F_{12}(s)]$$

$$= \frac{2\pi\, a_{612}\, T_{612}}{s}\,[\Delta F_6(s) - \Delta F_{12}(s)] + \frac{2\pi\, a_{712}\, T_{712}}{s}\,[\Delta F_7(s) - \Delta F_{12}(s)] + \frac{2\pi\, a_{812}\, T_{812}}{s}\,[\Delta F_8(s) - \Delta F_{12}(s)]$$

$$+ \frac{2\pi\, a_{912}\, T_{912}}{s}\,[\Delta F_9(s) - \Delta F_{12}(s)] + \frac{2\pi\, a_{1012}\, T_{1012}}{s}\,[\Delta F_{10}(s) - \Delta F_{12}(s)] + \frac{2\pi\, a_{1112}\, T_{1112}}{s}\,[\Delta F_{11}(s) - \Delta F_{12}(s)] \quad (2)$$

Area control error for area-1 with normal HVAC tie-line, $ACE_1(s) = B_1\,\Delta F_1(s) + \Delta P_{Tie1}(s) = B_1\,\Delta F_1(s) + \Delta P_{Tie16}(s)$
Area control error for area-2 with normal HVAC tie-line, $ACE_2(s) = B_2\,\Delta F_2(s) + \Delta P_{Tie2}(s) = B_2\,\Delta F_2(s) + \Delta P_{Tie26}(s)$
Area control error for area-3 with normal HVAC tie-line, $ACE_3(s) = B_3\,\Delta F_3(s) + \Delta P_{Tie3}(s) = B_3\,\Delta F_3(s) + \Delta P_{Tie36}(s)$
Area control error for area-4 with normal HVAC tie-line, $ACE_4(s) = B_4\,\Delta F_4(s) + \Delta P_{Tie4}(s) = B_4\,\Delta F_4(s) + \Delta P_{Tie46}(s)$
Area control error for area-5 with normal HVAC tie-line, $ACE_5(s) = B_5\,\Delta F_5(s) + \Delta P_{Tie5}(s) = B_5\,\Delta F_5(s) + \Delta P_{Tie56}(s)$
Area control error for area-6 (power grid-1) with normal HVAC tie-line, $ACE_6(s) = B_6\,\Delta F_6(s) + \Delta P_{Tie6}(s)$
Area control error for area-7 with normal HVAC tie-line, $ACE_7(s) = B_7\,\Delta F_7(s) + \Delta P_{Tie7}(s) = B_7\,\Delta F_7(s) + \Delta P_{Tie712}(s)$
Area control error for area-8 with normal HVAC tie-line, $ACE_8(s) = B_8\,\Delta F_8(s) + \Delta P_{Tie8}(s) = B_8\,\Delta F_8(s) + \Delta P_{Tie812}(s)$
Area control error for area-9 with normal HVAC tie-line, $ACE_9(s) = B_9\,\Delta F_9(s) + \Delta P_{Tie9}(s) = B_9\,\Delta F_9(s) + \Delta P_{Tie912}(s)$
Area control error for area-10 with normal HVAC tie-line, $ACE_{10}(s) = B_{10}\,\Delta F_{10}(s) + \Delta P_{Tie10}(s) = B_{10}\,\Delta F_{10}(s) + \Delta P_{Tie1012}(s)$
Area control error for area-11 with normal HVAC tie-line, $ACE_{11}(s) = B_{11}\,\Delta F_{11}(s) + \Delta P_{Tie11}(s) = B_{11}\,\Delta F_{11}(s) + \Delta P_{Tie1112}(s)$
Area control error for area-12 (power grid-2) with normal HVAC tie-line, $ACE_{12}(s) = B_{12}\,\Delta F_{12}(s) + \Delta P_{Tie12}(s)$.

The 12-Area Two Interconnected Thermal Power Grid with HVAC-HVDC Parallel Tie-Line as shown in figure 2.

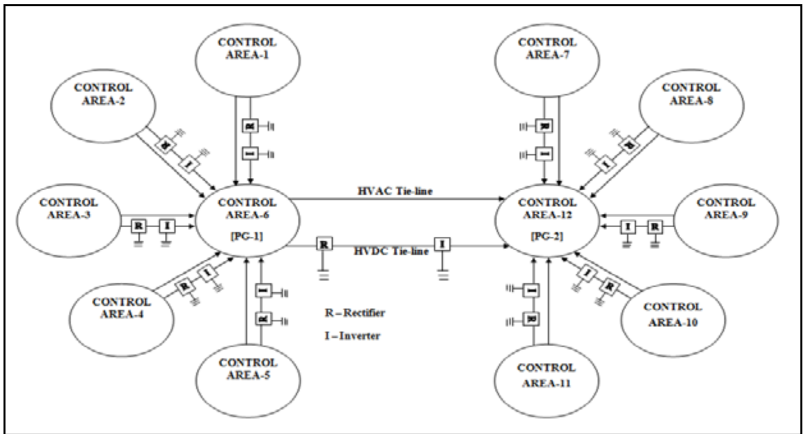

Fig.2 12-Area two interconnected thermal power grid with HVAC-HVDC parallel tie-line.

The power transfer from area-1 to area-6 (power grid-1), then the tie-line power equation is $\Delta P_{Tie1}(s) = \Delta P_{TieAC1}(s) + \Delta P_{TieDC1}(s) = \Delta P_{Tie16}(s) = \Delta P_{TieAC16}(s) + \Delta P_{TieDC16}(s)$

$$= \frac{2\pi\, T_{16}}{s} [\Delta F_1(s) - \Delta F_6(s)] + \frac{K_{DC1}}{s\, T_{DC1} + 1} [\Delta F_1(s) - \Delta F_6(s)]$$

The power transfer from area-2 to area-6 (power grid-1), then the tie-line power equation is $\Delta P_{Tie2}(s) = \Delta P_{TieAC2}(s) + \Delta P_{TieDC2}(s) = \Delta P_{Tie26}(s) = \Delta P_{TieAC26}(s) + \Delta P_{TieDC26}(s)$

$$= \frac{2\pi\, T_{26}}{s} [\Delta F_2(s) - \Delta F_6(s)] + \frac{K_{DC2}}{s\, T_{DC2} + 1} [\Delta F_2(s) - \Delta F_6(s)]$$

The power transfer from area-3 to area-6 (power grid-1), then the tie-line power equation is $\Delta P_{Tie3}(s) = \Delta P_{TieAC3}(s) + \Delta P_{TieDC3}(s) = \Delta P_{Tie36}(s) = \Delta P_{TieAC36}(s) + \Delta P_{TieDC36}(s)$

$$= \frac{2\pi\, T_{36}}{s} [\Delta F_3(s) - \Delta F_6(s)] + \frac{K_{DC3}}{s\, T_{DC3} + 1} [\Delta F_3(s) - \Delta F_6(s)]$$

The power transfer from area-4 to area-6 (power grid-1), then the tie-line power equation is $\Delta P_{Tie4}(s) = \Delta P_{TieAC4}(s) + \Delta P_{TieDC4}(s) = \Delta P_{Tie46}(s) = \Delta P_{TieAC46}(s) + \Delta P_{TieDC46}(s)$

$$= \frac{2\pi\, T_{46}}{s} [\Delta F_4(s) - \Delta F_6(s)] + \frac{K_{DC4}}{s\, T_{DC4} + 1} [\Delta F_4(s) - \Delta F_6(s)]$$

The power transfer from area-5 to area-6 (power grid-1), then the tie-line power equation is $\Delta P_{Tie5}(s) = \Delta P_{TieAC5}(s) + \Delta P_{TieDC5}(s) = \Delta P_{Tie56}(s) = \Delta P_{TieAC56}(s) + \Delta P_{TieDC56}(s)$

$$= \frac{2\pi\, T_{56}}{s} [\Delta F_5(s) - \Delta F_6(s)] + \frac{K_{DC5}}{s\, T_{DC5} + 1} [\Delta F_5(s) - \Delta F_6(s)]$$

The power transfer from area-7 to area-12 (power grid-2), then the tie-line power equation is $\Delta P_{Tie7}(s) = \Delta P_{TieAC7}(s) + \Delta P_{TieDC7}(s) = \Delta P_{Tie712}(s) = \Delta P_{TieAC712}(s) + \Delta P_{TieDC712}(s)$

$$= \frac{2\pi\, T_{712}}{s} [\Delta F_7(s) - \Delta F_{12}(s)] + \frac{K_{DC7}}{s\, T_{DC7} + 1} [\Delta F_7(s) - \Delta F_{12}(s)]$$

The power transfer from area-8 to area-12 (power grid-2), then the tie-line power equation is $\Delta P_{Tie8}(s) = \Delta P_{TieAC8}(s) + \Delta P_{TieDC8}(s) = \Delta P_{Tie812}(s) = \Delta P_{TieAC812}(s) + \Delta P_{TieDC812}(s)$

$$= \frac{2\pi\, T_{812}}{s} [\Delta F_8(s) - \Delta F_{12}(s)] + \frac{K_{DC8}}{s\, T_{DC8} + 1} [\Delta F_8(s) - \Delta F_{12}(s)]$$

The power transfer from area-9 to area-12 (power grid-2), then the tie-line power equation is $\Delta P_{Tie9}(s) = \Delta P_{TieAC9}(s) + \Delta P_{TieDC9}(s) = \Delta P_{Tie912}(s) = \Delta P_{TieAC912}(s) + \Delta P_{TieDC912}(s)$

$$= \frac{2\pi\, T_{912}}{s} [\Delta F_9(s) - \Delta F_{12}(s)] + \frac{K_{DC9}}{s\, T_{DC9} + 1} [\Delta F_9(s) - \Delta F_{12}(s)]$$

The power transfer from area-10 to area-12 (power grid-2), then the tie-line power equation is $\Delta P_{Tie10}(s) = \Delta P_{TieAC10}(s) + \Delta P_{TieDC10}(s) = \Delta P_{Tie1012}(s) = \Delta P_{TieAC1012}(s) + \Delta P_{TieDC1012}(s)$

$$= \frac{2\pi\, T_{1012}}{s} [\Delta F_{10}(s) - \Delta F_{12}(s)] + \frac{K_{DC10}}{s\, T_{DC10} + 1} [\Delta F_{10}(s) - \Delta F_{12}(s)]$$

The power transfer from area-11 to area-12 (power grid-2), then the tie-line power equation is $\Delta P_{Tie11}(s) = \Delta P_{TieAC11}(s) + \Delta P_{TieDC11}(s) = \Delta P_{Tie1112}(s) = \Delta P_{TieAC1112}(s) + \Delta P_{TieDC1112}(s)$

$$= \frac{2\pi\, T_{1112}}{s} [\Delta F_{11}(s) - \Delta F_{12}(s)] + \frac{K_{DC11}}{s\, T_{DC11} + 1} [\Delta F_{11}(s) - \Delta F_{12}(s)]$$

The tie-line power equation of power grid-1 (control area-6) is $\Delta P_{Tie6}(s)$, then
$\Delta P_{Tie6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s)$
Where $\Delta P_{TieAC6}(s)$ and $\Delta P_{TieDC6}(s)$ are,

$$\Delta P_{TieAC6}(s) = a_{16}\,\Delta P_{TieAC1}(s) + a_{26}\,\Delta P_{TieAC2}(s) + a_{36}\,\Delta P_{TieAC3}(s) + a_{46}\,\Delta P_{TieAC4}(s) + a_{56}\,\Delta P_{TieAC5}(s) + \Delta P_{TieAC612}(s)$$

[Here $\Delta P_{Tie612AC}(s) \neq \Delta P_{Tie6AC}(s)$]

$$= a_{16}\,\Delta P_{TieAC16}(s) + a_{26}\,\Delta P_{TieAC26}(s) + a_{36}\,\Delta P_{TieAC36}(s) + a_{46}\,\Delta P_{TieAC46}(s) + a_{56}\,\Delta P_{TieAC56}(s) + \Delta P_{TieAC612}(s)$$

$$= \frac{2\pi}{s}\left[\sum_{i=1,2,3,4,5} a_{i6}T_{i6}\,\Delta F_i(s) - \sum_{i=1,2,3,4,5} a_{i6}T_{i6}\,\Delta F_6(s)\right] + \Delta P_{TieAC612}(s)$$

$$= \frac{2\pi\, a_{16}T_{16}}{s}[\Delta F_1(s) - \Delta F_6(s)] + \frac{2\pi\, a_{26}T_{26}}{s}[\Delta F_2(s) - \Delta F_6(s)] + \frac{2\pi\, a_{36}T_{36}}{s}[\Delta F_3(s) - \Delta F_6(s)] + \frac{2\pi\, a_{46}T_{46}}{s}[\Delta F_4(s) - \Delta F_6(s)] + \frac{2\pi\, a_{56}T_{56}}{s}[\Delta F_5(s) - \Delta F_6(s)] + \frac{2\pi\, T_{612}}{s}[\Delta F_6(s) - \Delta F_{12}(s)] \quad (3)$$

$$\Delta P_{TieDC6}(s) = a_{16}\,\Delta P_{TieDC1}(s) + a_{26}\,\Delta P_{TieDC2}(s) + a_{36}\,\Delta P_{TieDC3}(s) + a_{46}\,\Delta P_{TieDC4}(s) + a_{56}\,\Delta P_{TieDC5}(s) + \Delta P_{TieDC612}(s)$$

[Here $\Delta P_{Tie612DC}(s) \neq \Delta P_{Tie6DC}(s)$]

$$= a_{16}\,\Delta P_{TieDC16}(s) + a_{26}\,\Delta P_{TieDC26}(s) + a_{36}\,\Delta P_{TieDC36}(s) + a_{46}\,\Delta P_{TieDC46}(s) + a_{56}\,\Delta P_{TieDC56}(s) + \Delta P_{TieDC612}(s)$$

$$= \frac{a_{16}\,K_{DC1}}{s\,T_{DC1}+1}[\Delta F_1(s) - \Delta F_6(s)] + \frac{a_{26}\,K_{DC2}}{s\,T_{DC2}+1}[\Delta F_2(s) - \Delta F_6(s)] + \frac{a_{36}\,K_{DC3}}{s\,T_{DC3}+1}[\Delta F_3(s) - \Delta F_6(s)] + \frac{a_{46}\,K_{DC4}}{s\,T_{DC4}+1}[\Delta F_4(s) - \Delta F_6(s)] + \frac{a_{56}\,K_{DC5}}{s\,T_{DC5}+1}[\Delta F_5(s) - \Delta F_6(s)] + \frac{K_{DC6}}{s\,T_{DC6}+1}[\Delta F_6(s) - \Delta F_{12}(s)] \quad (4)$$

The tie-line power equation of power grid -2 (control area-12) is $\Delta P_{Tie12}(s)$, then

$\Delta P_{Tie12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s)$

Where $\Delta P_{TieAC12}(s)$ and $\Delta P_{TieDC12}(s)$ are,

$$\Delta P_{TieAC12}(s) = a_{612}\,\Delta P_{TieAC612}(s) + a_{712}\,\Delta P_{TieAC7}(s) + a_{812}\,\Delta P_{TieAC8}(s) + a_{912}\,\Delta P_{TieAC9}(s) + a_{1012}\,\Delta P_{TieAC10}(s) + a_{1112}\,\Delta P_{TieAC11}(s)$$

[Here $\Delta P_{TieAC612}(s) \neq \Delta P_{TieAC6}(s)$]

$$= a_{612}\,\Delta P_{TieAC612}(s) + a_{712}\,\Delta P_{TieAC712}(s) + a_{812}\,\Delta P_{TieAC812}(s) + a_{912}\,\Delta P_{TieAC912}(s) + a_{1012}\,\Delta P_{TieAC1012}(s) + a_{1112}\,\Delta P_{TieAC1112}(s)$$

$$= \frac{2\pi}{s}\left[\sum_{k=6,7,8,9,10,11} a_{k12}\,T_{k12}\,\Delta F_k(s) - \sum_{k=6,7,8,9,10,11} a_{k12}\,T_{k12}\,\Delta F_{12}(s)\right]$$

$$= \frac{2\pi\, a_{612}\,T_{612}}{s}[\Delta F_6(s) - \Delta F_{12}(s)] + \frac{2\pi\, a_{712}\,T_{712}}{s}[\Delta F_7(s) - \Delta F_{12}(s)] + \frac{2\pi\, a_{812}\,T_{812}}{s}[\Delta F_8(s) - \Delta F_{12}(s)] + \frac{2\pi\, a_{912}\,T_{912}}{s}[\Delta F_9(s) - \Delta F_{12}(s)] + \frac{2\pi\, a_{1012}\,T_{1012}}{s}[\Delta F_{10}(s) - \Delta F_{12}(s)] + \frac{2\pi\, a_{1112}\,T_{1112}}{s}[\Delta F_{11}(s) - \Delta F_{12}(s)] \quad (5)$$

$$\Delta P_{TieDC12}(s) = a_{612}\,\Delta P_{TieDC612}(s) + a_{712}\,\Delta P_{TieDC7}(s) + a_{812}\,\Delta P_{TieDC8}(s) + a_{912}\,\Delta P_{TieDC9}(s) + a_{1012}\,\Delta P_{TieDC10}(s) + a_{1112}\,\Delta P_{TieDC11}(s)$$

[Here $\Delta P_{TieDC612}(s) \neq \Delta P_{TieDC6}(s)$]

$$= a_{612}\,\Delta P_{TieDC612}(s) + a_{712}\,\Delta P_{TieDC712}(s) + a_{812}\,\Delta P_{TieDC812}(s) + a_{912}\,\Delta P_{TieDC912}(s) + a_{1012}\,\Delta P_{TieDC1012}(s) + a_{1112}\,\Delta P_{TieDC1112}(s)$$

$$= \frac{a_{612}\,K_{DC6}}{s\,T_{DC6}+1}[\Delta F_6(s) - \Delta F_{12}(s)] + \frac{a_{712}\,K_{DC7}}{s\,T_{DC7}+1}[\Delta F_7(s) - \Delta F_{12}(s)] + \frac{a_{812}\,K_{DC8}}{s\,T_{DC8}+1}[\Delta F_8(s) - \Delta F_{12}(s)] + \frac{a_{912}\,K_{DC9}}{s\,T_{DC9}+1}[\Delta F_9(s) - \Delta F_{12}(s)] + \frac{a_{1012}\,K_{DC10}}{s\,T_{DC10}+1}[\Delta F_{10}(s) - \Delta F_{12}(s)] + \frac{a_{1112}\,K_{DC11}}{s\,T_{DC11}+1}[\Delta F_{11}(s) - \Delta F_{12}(s)] \quad (6)$$

Area control error for area-1 with HVAC-HVDC parallel tie-line,

$ACE_1(s) = B_1\,\Delta F_1(s) + \Delta P_{Tie1}(s) = B_1\,\Delta F_1(s) + [\Delta P_{TieAC1}(s) + \Delta P_{TieDC1}(s)]$

$= B_1\,\Delta F_1(s) + \Delta P_{Tie16}(s) = B_1\,\Delta F_1(s) + [\Delta P_{TieAC16}(s) + \Delta P_{TieDC16}(s)]$

Area control error for area-2 with HVAC-HVDC parallel tie-line,

$ACE_2(s) = B_2\,\Delta F_2(s) + \Delta P_{Tie2}(s) = B_2\,\Delta F_2(s) + [\Delta P_{TieAC2}(s) + \Delta P_{TieDC2}(s)]$

$= B_2\,\Delta F_2(s) + \Delta P_{Tie26}(s) = B_2\,\Delta F_2(s) + [\Delta P_{TieAC26}(s) + \Delta P_{TieDC26}(s)]$

Area control error for area-3 with HVAC-HVDC parallel tie-line,

$ACE_3(s) = B_3\,\Delta F_3(s) + \Delta P_{Tie3}(s) = B_3\,\Delta F_3(s) + [\Delta P_{TieAC3}(s) + \Delta P_{TieDC3}(s)]$

$= B_3\,\Delta F_3(s) + \Delta P_{Tie36}(s) = B_3\,\Delta F_3(s) + [\Delta P_{TieAC36}(s) + \Delta P_{TieDC36}(s)]$

Area control error for area-4 with HVAC-HVDC parallel tie-line,

$ACE_4(s) = B_4\,\Delta F_4(s) + \Delta P_{Tie4}(s) = B_4\,\Delta F_4(s) + [\Delta P_{TieAC4}(s) + \Delta P_{TieDC4}(s)]$

$= B_4\,\Delta F_4(s) + \Delta P_{Tie46}(s) = B_4\,\Delta F_4(s) + [\Delta P_{TieAC46}(s) + \Delta P_{TieDC46}(s)]$

Area control error for area-5 with HVAC-HVDC parallel tie-line,

$ACE_5(s) = B_5\,\Delta F_5(s) + \Delta P_{Tie5}(s) = B_5\,\Delta F_5(s) + [\Delta P_{TieAC5}(s) + \Delta P_{TieDC5}(s)]$

$= B_5\,\Delta F_5(s) + \Delta P_{Tie56}(s) = B_5\,\Delta F_5(s) + [\Delta P_{TieAC56}(s) + \Delta P_{TieDC56}(s)]$

Area control error for area-6 (power grid-1) with HVAC-HVDC parallel tie-line,

$ACE_6(s) = B_6\,\Delta F_6(s) + \Delta P_{Tie6}(s) = B_6\,\Delta F_6(s) + [\Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s)]$

Area control error for area-7 with HVAC-HVDC parallel tie-line,

$ACE_7(s) = B_7\,\Delta F_7(s) + \Delta P_{Tie7}(s) = B_7\,\Delta F_7(s) + [\Delta P_{TieAC7}(s) + \Delta P_{TieDC7}(s)]$

$= B_7\,\Delta F_7(s) + \Delta P_{Tie712}(s) = B_2\,\Delta F_2(s) + [\Delta P_{TieAC712}(s) + \Delta P_{TieDC712}(s)]$

Area control error for area-8 with HVAC-HVDC parallel tie-line,

$ACE_8(s) = B_8\,\Delta F_8(s) + \Delta P_{Tie8}(s) = B_8\,\Delta F_8(s) + [\Delta P_{TieAC8}(s) + \Delta P_{TieDC8}(s)]$

$= B_8\,\Delta F_8(s) + \Delta P_{Tie812}(s) = B_8\,\Delta F_8(s) + [\Delta P_{TieAC812}(s) + \Delta P_{TieDC812}(s)]$

Area control error for area-9 with HVAC-HVDC parallel tie-line,

$ACE_9(s) = B_9\ \Delta F_9(s) + \Delta P_{Tie9}(s) = B_9\ \Delta F_9(s) + [\Delta P_{TieAC9}(s) + \Delta P_{TieDC9}(s)]$

$= B_9\ \Delta F_9(s) + \Delta P_{Tie912}(s) = B_9\ \Delta F_9(s) + [\Delta P_{TieAC912}(s) + \Delta P_{TieDC912}(s)]$

Area control error for area-10 with HVAC-HVDC parallel tie-line,

$ACE_{10}(s) = B_{10}\ \Delta F_{10}(s) + \Delta P_{Tie10}(s) = B_{10}\ \Delta F_{10}(s) + [\Delta P_{TieAC10}(s) + \Delta P_{TieDC10}(s)]$

$= B_{10}\ \Delta F_{10}(s) + \Delta P_{Tie1012}(s) = B_{10}\ \Delta F_{10}(s) + [\Delta P_{TieAC1012}(s) + \Delta P_{TieDC1012}(s)]$

Area control error for area-11 with HVAC-HVDC parallel tie-line,

$ACE_{11}(s) = B_{11}\ \Delta F_{11}(s) + \Delta P_{Tie11}(s) = B_{11}\ \Delta F_{11}(s) + [\Delta P_{TieAC11}(s) + \Delta P_{TieDC11}(s)]$

$= B_{11}\ \Delta F_{11}(s) + \Delta P_{Tie1112}(s) = B_{11}\ \Delta F_{11}(s) + [\Delta P_{TieAC1112}(s) + \Delta P_{TieDC1112}(s)]$

Area control error for area-12 (power grid-2) with HVAC-HVDC parallel tie-line,

$ACE_{12}(s) = B_{12}\ \Delta F_{12}(s) + \Delta P_{Tie12}(s) = B_{12}\ \Delta F_{12}(s) + [\Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s)]$.

B. 12-Area Two Interconnected Thermal Power Grid with Flexible AC Transmission System (FACTS) Tie-Line

The 12-Area Two Interconnected Thermal Power Grid with FACTS Tie-Line as shown in figure 3.

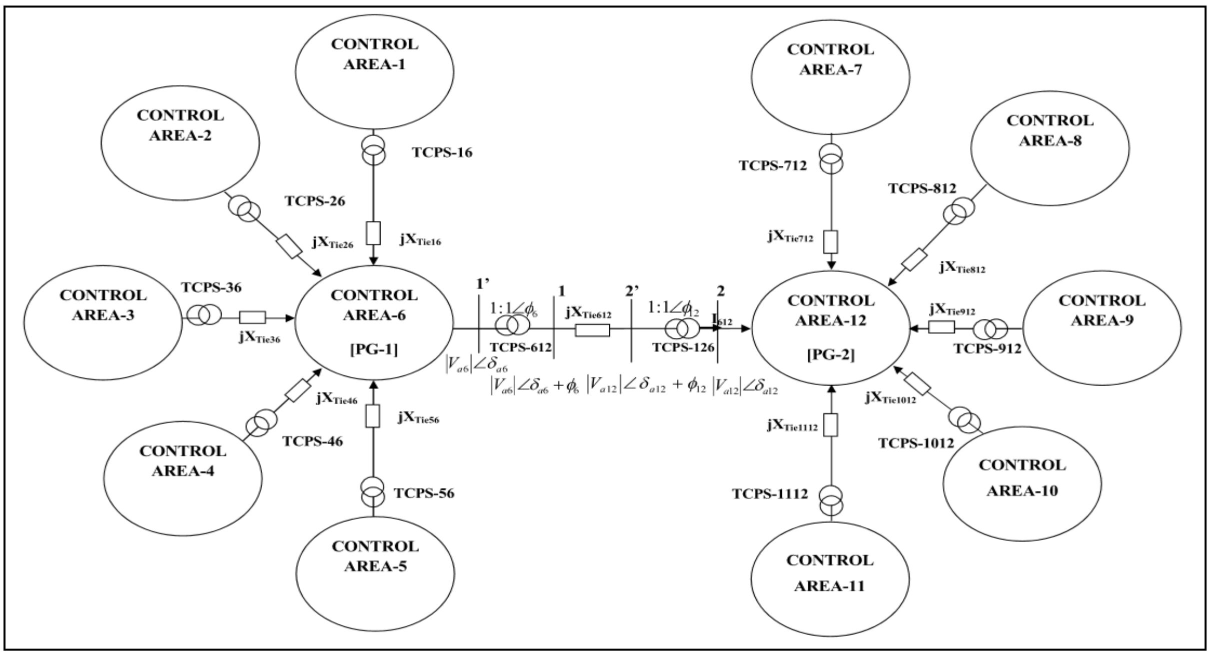

Fig.3 12-Area two interconnected thermal power grid with Flexible AC Transmission System (FACTS) tie-line.

For interconnection of two power grids, two TCPS is applied in series with HVAC tie-line between two power grids in each end of HVAC tie-line. And also for interconnection of individual areas to the each power grids, only one TCPS is applied in series with HVAC tie-line, this is shown in figure-(3).

Power Transfer from Power Grid-1 to Power Grid-2: Without TCPS612 in a conventional interconnected thermal power grid system, the incremental tie line power flow from power grid-1 to power grid-2 $\Delta P_{Tie612wps}(s)$ is

$$\Delta P_{Tie612wps}(s) = \frac{2\pi T_{612wps}}{s}\,[\Delta F_6(s) - \Delta F_{12}(s)] \text{ where,}$$

T_{612wps} = Synchronizing power coefficient without TCPS612

$\Delta F_6(s)$ = Frequency deviation of area-6 & $\Delta F_{12}(s)$ = Frequency deviation of area-12

Current flowing from area-6 to area-12

$$I_{612} = \frac{|V_{ar6}|\angle(\delta_{ar6} + \phi_6) - |V_{ar12}|\angle\delta_{ar12}}{jX_{tie612}}$$

Now, the tie line power equation is

$$P_{Tie612} - jQ_{Tie612} = (V_{ar6})^* I_{612} = [|V_{ar6}|\angle-(\delta_{ar6} + \phi_6)]\, I_{612}$$

$$= [|V_{ar6}|\angle-(\delta_{ar6} + \phi_6)]\, \frac{|V_{ar6}|\angle(\delta_{ar6} + \phi_6) - |V_{ar12}|\angle\delta_{ar12}}{jX_{tie612}}$$

$$= \frac{|V_{ar6}|\,|V_{ar12}|}{X_{tie612}} \operatorname{Sin}(\delta_{ar6} - \delta_{ar12} + \phi_6) - \frac{j\,|V_{ar6}|^2 - |V_{ar6}|\,|V_{ar12}| \cos(\delta_{ar6} - \delta_{ar12} + \phi_6)}{X_{tie612}}$$

The real part of the above equation $P_{Tie612} = \frac{|V_{ar6}|\,|V_{ar12}|}{X_{tie612}} \operatorname{Sin}(\delta_{ar6} - \delta_{ar12} + \phi_6)$

Moving δ_{ar6}, δ_{ar12} & ϕ_6 from their nominal values δ°_{ar6}, δ°_{ar12} & ϕ°_6 respectively

$$\Delta P_{Tie612} = \frac{|V_{ar6}|\,|V_{ar12}|}{X_{tie612}} \operatorname{Cos}(\delta^{\circ}_{ar6} - \delta^{\circ}_{ar12} + \phi^{\circ}_6) * \operatorname{Sin}(\Delta\delta_{ar6} - \Delta\delta_{ar12} + \Delta\phi_6)$$

Since $(\Delta\delta_{ar6} - \Delta\delta_{ar12} + \Delta\phi_6)$ is very small, therefore $\text{Sin}(\Delta\delta_{ar6} - \Delta\delta_{ar12} + \Delta\phi_6) \approx (\Delta\delta_{ar6} - \Delta\delta_{ar12} + \Delta\phi_6)$

$\Delta P_{Tie612} = \frac{|V_{ar6}|\ |V_{ar12}|}{X_{tie612}} \text{Cos}(\delta^\circ_{ar6} - \delta^\circ_{ar12} + \phi^\circ_6) * (\Delta\delta_{ar6} - \Delta\delta_{ar12} + \Delta\phi_6)$

Let T_{612} be the synchronizing coefficient with TCPS612, $T_{612} = \frac{|V_{ar6}|\ |V_{ar12}|}{X_{tie612}} \text{Cos}(\delta^\circ_{ar6} - \delta^\circ_{ar12} + \phi^\circ_6)$

So that $\Delta P_{Tie612} = T_{612} (\Delta\delta_{ar6} - \Delta\delta_{ar12} + \Delta\phi_6) = T_{612} (\Delta\delta_{ar6} - \Delta\delta_{ar12}) + T_{612} \Delta\phi_6$

Where $\Delta\delta_{ar6} = 2\pi\int_0^t \Delta F_6\, dt$ & $\Delta\delta_{ar12} = 2\pi\int_0^t \Delta F_{12}\, dt$

$\Delta P_{Tie612} = T_{612} (2\pi\int_0^t \Delta F_6\, dt - 2\pi\int_0^t \Delta F_{12}\, dt) + T_{612} \Delta\phi_6$

Taking Laplace Transforms of above equation $\Delta P_{Tie612}(s) = \frac{2\pi T_{612}}{s} [\Delta F_6(s) - \Delta F_{12}(s)] + T_{612}\, \Delta\phi_6(s)$

But TCPS126 is present in series at other end of tie-line in side of Power Grid-2, so that the power flow from Power Grid-1 to Power Grid-2 is now becomes

$\Delta P_{Tie612}(s) = \frac{2\pi T_{612}}{s}[\Delta F_6(s) - \Delta F_{12}(s)] + T_{612}\Delta\phi_6(s) - T_{126}\, \Delta\phi_{12}(s)$ (7)

In above equation the tie line power flow can be controlled by controlling the phase shifter angle $\Delta\phi_6(s)$ of TCPS612 & $\Delta\phi_{12}(s)$ of TCPS126. The phase shifter angle $\Delta\phi_6(s)$ is,

$\Delta\phi_6(s) = \frac{K_{\phi6}}{1+sT_{\phi6}} \Delta\text{Error}(s) = \frac{K_{\phi6}}{1+sT_{\phi6}} \Delta F_6(s)$

Where $K_{\phi6}$ = Gain & $T_{\phi6}$ = Time constant of TCPS612

$\Delta\text{Error}(s) = \Delta F_6(s)$ = Frequency deviation of area-6

The phase shifter angle $\Delta\phi_{12}(s)$ is,

$\Delta\phi_{12}(s) = \frac{K_{\phi12}}{1+sT_{\phi12}} \Delta\text{Error}(s) = \frac{K_{\phi12}}{1+sT_{\phi12}} \Delta F_{12}(s)$

Where $K_{\phi12}$ = Gain & $T_{\phi12}$ = Time constant of TCPS126

$\Delta\text{Error}(s) = \Delta F_{12}(s)$ = Frequency deviation of area-12

Also,

$\Delta P_{Tie16}(s) = \frac{2\pi T_{16}}{s} [\Delta F_1(s) - \Delta F_6(s)] + T_{16}\, \Delta\phi_1(s)$, $\Delta P_{Tie26}(s) = \frac{2\pi T_{26}}{s} [\Delta F_2(s) - \Delta F_6(s)] + T_{26}\, \Delta\phi_2(s)$,

$\Delta P_{Tie36}(s) = \frac{2\pi T_{36}}{s} [\Delta F_3(s) - \Delta F_6(s)] + T_{36}\, \Delta\phi_3(s)$, $\Delta P_{Tie46}(s) = \frac{2\pi T_{46}}{s} [\Delta F_4(s) - \Delta F_6(s)] + T_{46}\, \Delta\phi_4(s)$,

$\Delta P_{Tie56}(s) = \frac{2\pi T_{56}}{s} [\Delta F_5(s) - \Delta F_6(s)] + T_{56}\, \Delta\phi_5(s)$, $\Delta P_{Tie712}(s) = \frac{2\pi T_{712}}{s} [\Delta F_7(s) - \Delta F_{12}(s)] + T_{712}\, \Delta\phi_7(s)$,

$\Delta P_{Tie812}(s) = \frac{2\pi T_{812}}{s} [\Delta F_8(s) - \Delta F_{12}(s)] + T_{812}\, \Delta\phi_8(s)$, $\Delta P_{Tie912}(s) = \frac{2\pi T_{912}}{s} [\Delta F_9(s) - \Delta F_{12}(s)] + T_{912}\, \Delta\phi_9(s)$,

$\Delta P_{Tie1012}(s) = \frac{2\pi T_{1012}}{s} [\Delta F_{10}(s) - \Delta F_{12}(s)] + T_{1012}\, \Delta\phi_{10}(s)$, $\Delta P_{Tie1112}(s) = \frac{2\pi T_{1112}}{s} [\Delta F_{11}(s) - \Delta F_{12}(s)] + T_{1112}\, \Delta\phi_{11}(s)$.

The tie-line power equation of power grid -1 (control area-6) is $\Delta P_{Tie6}(s)$, then

$\Delta P_{Tie6}(s) = a_{16}\, \Delta P_{Tie1}(s) + a_{26}\, \Delta P_{Tie2}(s) + a_{36}\, \Delta P_{Tie3}(s) + a_{46}\, \Delta P_{Tie4}(s) + a_{56}\, \Delta P_{Tie5}(s) + \Delta P_{Tie612}(s)$

[Here $\Delta P_{Tie612}(s) \neq \Delta P_{Tie6}(s)$]

$= a_{16}\, \Delta P_{Tie16}(s) + a_{26}\, \Delta P_{Tie26}(s) + a_{36}\, \Delta P_{Tie36}(s) + a_{46}\, \Delta P_{Tie46}(s) + a_{56}\, \Delta P_{Tie56}(s) + \Delta P_{Tie612}(s)$

$= \frac{2\pi}{s} [\sum_{i=1,2,3,4,5} a_{i6} T_{i6}\, \Delta F_i(s) - \sum_{i=1,2,3,4,5} a_{i6} T_{i6}\, \Delta F_6(s)] + \sum_{i=1,2,3,4,5} a_{i6} T_{i6}\, \Delta\phi_i(s) + \Delta P_{Tie612}(s)$

$= a_{16} [\frac{2\pi T_{16}}{s} \{\Delta F_1(s) - \Delta F_6(s)\} + T_{16}\Delta\phi_1(s)] + a_{26} [\frac{2\pi T_{26}}{s} \{\Delta F_2(s) - \Delta F_6(s)\} + T_{26}\Delta\phi_2(s)]$

$+ a_{36} [\frac{2\pi T_{36}}{s}\{\Delta F_3(s) - \Delta F_6(s)\} + T_{36}\Delta\phi_3(s)] + a_{46} [\frac{2\pi T_{46}}{s} \{\Delta F_4(s) - \Delta F_6(s)\} + T_{46}\Delta\phi_4(s)]$

$+ a_{56} [\frac{2\pi T_{56}}{s}\{\Delta F_5(s) - \Delta F_6(s)\} + T_{56}\Delta\phi_5(s)] + [\frac{2\pi T_{612}}{s} \{\Delta F_6(s) - \Delta F_{12}(s)\} + T_{612}\Delta\phi_6(s) - T_{126}\, \Delta\phi_{12}(s)]$ (8)

The tie-line power equation of power grid -2 (control area-12) is $\Delta P_{Tie12}(s)$, then

$\Delta P_{Tie12}(s) = a_{612}\, \Delta P_{Tie612}(s) + a_{712}\, \Delta P_{Tie7}(s) + a_{812}\, \Delta P_{Tie8}(s) + a_{912}\, \Delta P_{Tie9}(s) + a_{1012}\, \Delta P_{Tie10}(s) + a_{1112}\, \Delta P_{Tie11}(s)$

[Here $\Delta P_{Tie612}(s) \neq \Delta P_{Tie6}(s)$]

$= a_{612}\, \Delta P_{Tie612}(s) + a_{712}\, \Delta P_{Tie712}(s) + a_{812}\, \Delta P_{Tie812}(s) + a_{912}\, \Delta P_{Tie912}(s) + a_{1012}\, \Delta P_{Tie1012}(s) + a_{1112}\, \Delta P_{Tie1112}(s)$

$= a_{612}\, \Delta P_{Tie612}(s) + \frac{2\pi}{s} [\sum_{k=7,8,9,10,11} a_{k12} T_{k12} \Delta F_k(s) - \sum_{k=7,8,9,10,11} a_{k12} T_{k12} \Delta F_{12}(s)]$

$+ \sum_{k=7,8,9,10,11} a_{k12} T_{k12}\, \Delta\phi_k(s)$

$= a_{612} [\frac{2\pi T_{612}}{s} \{\Delta F_6(s) - \Delta F_{12}(s)\} + T_{612}\, \Delta\phi_6(s) - T_{126}\, \Delta\phi_{12}(s)] + a_{712} [\frac{2\pi T_{712}}{s} \{\Delta F_7(s) - \Delta F_{12}(s)\}$

$+ T_{712}\, \Delta\phi_7(s)] + a_{812} [\frac{2\pi T_{812}}{s} \{\Delta F_8(s) - \Delta F_{12}(s)\} + T_{812}\, \Delta\phi_8(s)] + a_{912} [\frac{2\pi T_{912}}{s} \{\Delta F_9(s) - \Delta F_{12}(s)\}$

$+ T_{912}\, \Delta\phi_9(s)] + a_{1012} [\frac{2\pi T_{1012}}{s} \{\Delta F_{10}(s) - \Delta F_{12}(s)\} + T_{1012}\, \Delta\phi_{10}(s)] + a_{1112} [\frac{2\pi T_{1112}}{s} \{\Delta F_{11}(s) - \Delta F_{12}(s)\}$

$+ T_{1112}\Delta\phi_{11}(s)]$ (9)

Area control error for area-1 with FACTS tie-line, $ACE_1(s) = B_1\, \Delta F_1(s) + \Delta P_{Tie1}(s) = B_1\, \Delta F_1(s) + \Delta P_{Tie16}(s)$

Area control error for area-2 with FACTS tie-line, $ACE_2(s) = B_2\, \Delta F_2(s) + \Delta P_{Tie2}(s) = B_2\, \Delta F_2(s) + \Delta P_{Tie26}(s)$

Area control error for area-3 with FACTS tie-line, $ACE_3(s) = B_3\, \Delta F_3(s) + \Delta P_{Tie3}(s) = B_3\, \Delta F_3(s) + \Delta P_{Tie36}(s)$

Area control error for area-4 with FACTS tie-line, $ACE_4(s) = B_4\, \Delta F_4(s) + \Delta P_{Tie4}(s) = B_4\, \Delta F_4(s) + \Delta P_{Tie46}(s)$

Area control error for area-5 with FACTS tie-line, $ACE_5(s) = B_5\, \Delta F_5(s) + \Delta P_{Tie5}(s) = B_5\, \Delta F_5(s) + \Delta P_{Tie56}(s)$

Area control error for area-6 (power grid-1) with FACTS tie-line, $ACE_6(s) = B_6\, \Delta F_6(s) + \Delta P_{Tie6}(s)$

Area control error for area-7 with FACTS tie-line, $ACE_7(s) = B_7\, \Delta F_7(s) + \Delta P_{Tie7}(s) = B_7\, \Delta F_7(s) + \Delta P_{Tie712}(s)$

Area control error for area-8 with FACTS tie-line, $ACE_8(s) = B_8\, \Delta F_8(s) + \Delta P_{Tie8}(s) = B_8\, \Delta F_8(s) + \Delta P_{Tie812}(s)$

Area control error for area-9 with FACTS tie-line, $ACE_9(s) = B_9\ \Delta F_9(s) + \Delta P_{Tie9}(s) = B_9\ \Delta F_9(s) + \Delta P_{Tie912}(s)$

Area control error for area-10 with FACTS tie-line, $ACE_{10}(s) = B_{10}\ \Delta F_{10}(s) + \Delta P_{Tie10}(s) = B_{10}\ \Delta F_{10}(s) + \Delta P_{Tie1012}(s)$

Area control error for area-11 with FACTS tie-line, $ACE_{11}(s) = B_{11}\ \Delta F_{11}(s) + \Delta P_{Tie11}(s) = B_{11}\ \Delta F_{11}(s) + \Delta P_{Tie1112}(s)$

Area control error for area-12 (power grid-2) with FACTS tie-line, $ACE_{12}(s) = B_{12}\ \Delta F_{12}(s) + \Delta P_{Tie12}(s)$.

C.12-Area Two Interconnected Thermal Power Grid Parameters with Different Tie-Line

The transfer function of various blocks in 12-area two interconnected thermal power grid with different is following:

Transfer function of load (machine) $P_{PS\ (i)}\ (s) = \frac{K_{PS(i)}}{sT_{PS(i)}+1}$

Transfer function of governor (boiler) $P_{B\ (i)}\ (s) = \frac{1}{sT_{G(i)}+1}$

Transfer function of turbine $P_{T\ (i)}\ (s) = \frac{1}{sT_{t(i)}+1}$

Transfer function of reheater $P_{RT\ (i)}\ (s) = \frac{s\ K_{R(i)}T_{R(i)}+1}{s\ T_{R(i)}+1}$

Transfer function of integral controller, $G_{Ci}(s) = \frac{Ki}{s}$

The control signal is, $\Delta P_i(s) = -[G_{Ci}(s).ACE_i(s)]$

The area control error $ACE_{(i)}(s) = B_{(i)}\ \Delta F_{(i)}(s) + \Delta P_{Tie(i)}(s)$

Transfer function of HVDC link = $\frac{K_{DC(i)}}{sT_{DC(i)}+1}$

In above equations i = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12.

Transfer function of Thyristor Control Phase Shifters is: $TCPS612 = T_{612}\ \frac{K_{\phi 6}}{1+sT_{\phi 6}}$ & $TCPS126 = T_{126}\ \frac{K_{\phi 12}}{1+sT_{\phi 12}}$

Rated capacity of control areas and two power grids in MW: $P_{r1} = P_{r2} = P_{r3} = P_{r4} = P_{r5} = P_{r6} = P_{r7} = P_{r8} = P_{r9} = P_{r10} = P_{r11} = P_{r12}$ = 2000MW & Base MVA = 2000MVA

Area capacity ratio $a_{16} = a_{26} = a_{36} = a_{46} = a_{56} = a_{612} = a_{712} = a_{812} = a_{912} = a_{1012} = a_{1112} = -1$

Maximum tie-line power P_{TieMAX} = 200 MW, Synchronizing coefficients T = 0.0868puMW/radian,

Bias constants B = 0.425puMW/Hz, Speed regulation of governors R = 2.4Hz/puMW,

Frequency of power system = 60Hz, Power system gain constants K_{PS} = 120Hz/puMW,

Power system time constants T_{PS} = 20sec, Turbine time constants T_t = 0.3sec,

Re-heater gain constants K_R = 0.5sec, Re-heater turbine time constants: T_R = 10sec.

HVDC-Link: Gain K_{DC} = 1 , Time constants T_{DC} = 0.2 sec & Capacity of HVDC-Link = 20 MW

TCPS: Gain K_{ϕ} = 1.5 rad/Hz & Time constants T_{ϕ} = 0.1sec

Phase shifter angle of TCPS: ϕ_{MAX} = 10° & ϕ_{MIN} = -10°

Load change in power grid-1: ΔP_{L6} = 0.01 p.u.

Value of integral control gain with Normal HVAC Tie-Line: $K_1 = K_2 = K_3 = K_4 = K_5 = K_6 = K_7 = K_8 = K_9 = K_{10} = K_{11} = K_{12} = 0.45$

Value of integral control gain with HVAC-HVDC Parallel Tie-Line:
$K_1 = K_2 = K_3 = K_4 = K_5 = K_6 = K_7 = K_8 = K_9 = K_{10} = K_{11} = K_{12} = 2.35$

Value of integral control gain with FACTS Tie-Line:
$K_1 = K_2 = K_3 = K_4 = K_5 = K_7 = K_8 = K_9 = K_{10} = K_{11} = 0.45$ & $K_6 = K_{12} = 1.81$.

(1) Tie-Line Power Calculation with Normal HVAC and FACTS Tie-Line: The tie-line power calculation with Normal HVAC & FACTS Tie-line are same and this is represented by following equations,

Power Grid-1 (Control Area-6): Power grid-1 is receiving 1000 MW power from its interconnected areas (area-1, area-2, area-3, area-4, area-5) and sending 200 MW power for power grid-2. We know $\Delta P_{Tie6}(s)$ is

$\Delta P_{Tie6}(s) = a_{16}\ \Delta P_{Tie16}(s) + a_{26}\ \Delta P_{Tie26}(s) + a_{36}\ \Delta P_{Tie36}(s) + a_{46}\ \Delta P_{Tie46}(s) + a_{56}\ \Delta P_{Tie56}(s) + \Delta P_{Tie612}(s)$

= [(-1) 200 + (-1) 200 + (-1) 200 + (-1) 200 + (-1) 200 + (-1) 200 + (-1) 200 + {200}]

= [(-1000) + {200}] = -800 MW

Negative sign shows the power grid-1 is receiving power from its interconnected areas.

Power Grid-2 (Control Area-12): Power Grid-2 receiving 200 MW power from Power Grid-1 and 1000 MW power from its interconnected areas (area-7, area-8, area-9, area-10, area-11). We know $\Delta P_{Tie12}(s)$ is

$\Delta P_{Tie12}(s) = a_{612}\ \Delta P_{Tie612}(s) + a_{712}\ \Delta P_{Tie712}(s) + a_{812}\ \Delta P_{Tie812}(s) + a_{912}\ \Delta P_{Tie912}(s) + a_{1012}\ \Delta P_{Tie1012}(s) + a_{1112}\ \Delta P_{Tie1112}(s)$

= [(-1) 200 + (-1) 200 + (-1) 200 + (-1) 200 + (-1) 200 + (-1) 200]

= [{-200} + (-1000)] = -1200 MW

Negative sign shows the power grid-2 is receiving power from power grid-1 and its interconnected areas.

(2) Tie-Line Power Calculation with HVAC-HVDC Parallel Tie-Line: The tie-line power calculation with HVAC-HVDC parallel tie-line is following,

Power Grid-1 (Control Area-6): Power grid-1 is receiving 1000 MW power from its interconnected areas (area-1, area-2, area-3, area-4, area-5) and sending 200 MW power for power grid-2. We know $\Delta P_{Tie6}(s)$ is

$\Delta P_{Tie6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s)$

Where $\Delta P_{TieAC6}(s)$ and $\Delta P_{TieDC6}(s)$ are,

$\Delta P_{TieAC6}(s) = a_{16}\ \Delta P_{TieAC16}(s) + a_{26}\ \Delta P_{TieAC26}(s) + a_{36}\ \Delta P_{TieAC36}(s) + a_{46}\ \Delta P_{TieAC46}(s) + a_{56}\ \Delta P_{TieAC56}(s) + \Delta P_{TieAC612}(s)$

= [(-1) 180 + (-1) 180 + (-1) 180 + (-1) 180 + (-1) 180 + {180}]

$= [\ (-900) + \{180\}\ ] = -720$ MW

$\Delta P_{TieDC6}(s) = a_{16}\ \Delta P_{TieDC16}(s) + a_{26}\ \Delta P_{TieDC26}(s) + a_{36}\ \Delta P_{TieDC36}(s) + a_{46}\ \Delta P_{TieDC46}(s) + a_{56}\ \Delta P_{TieDC56}(s) + \Delta P_{TieDC612}(s)$

$= [\ (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + \{20\}\ ]$

$= [\ (-100) + \{20\}] = -80$ MW

$\Delta P_{Tie6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s) = (-720) + (-80) = -800$ MW

Negative sign shows the power grid-1 is receiving power from its interconnected areas.

Power Grid-2 (Control Area-12): Power Grid-2 receiving 200 MW power from Power Grid-1 and 1000 MW power from its interconnected areas (area-7, area-8, area-9, area-10, area-11). We know $\Delta P_{Tie12}(s)$ is

$\Delta P_{Tie12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s)$

Where $\Delta P_{TieAC12}(s)$ and $\Delta P_{TieDC12}(s)$ are,

$\Delta P_{TieAC12}(s) = a_{612}\ \Delta P_{TieAC612}(s) + a_{712}\ \Delta P_{TieAC712}(s) + a_{812}\ \Delta P_{TieAC812}(s) + a_{912}\ \Delta P_{TieAC912}(s) + a_{1012}\ \Delta P_{TieAC1012}(s) + a_{1112}\ \Delta P_{TieAC1112}(s)$

$= [\ (-1)\ 180 + (-1)\ 180 + (-1)\ 180 + (-1)\ 180 + (-1)\ 180 + (-1)\ 180\ ]$

$= [\ \{-180\} + (-900)\ ] = -1080$ MW

$\Delta P_{TieDC12}(s) = a_{612}\ \Delta P_{TieDC612}(s) + a_{712}\ \Delta P_{TieDC712}(s) + a_{812}\ \Delta P_{TieDC812}(s) + a_{912}\ \Delta P_{TieDC912}(s) + a_{1012}\ \Delta P_{TieDC1012}(s) + a_{1112}\ \Delta P_{TieDC1112}(s)$

$= [\ (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ ] = [\ \{-20\} + (-100)\ ] = -120$ MW

$\Delta P_{Tie12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s) = (-1080) + (-120) = -1200$ MW

Negative sign shows the power grid-2 is receiving power from power grid-1 and its interconnected areas.

III. MATLAB SIMULINK MODEL OF 12-AREA TWO INTERCONNECTED THERMAL POWER GRID WITH DIFFERENT TIE-LINE

The simulation is done in MATLAB Software-Math Works, Volume Version 8.1.0.604 (R2013a).

A. The SIMULINK MODEL of 12-Area Two Interconnected Thermal Power Grid with Normal HVAC Tie-Line as shown in figure 4.

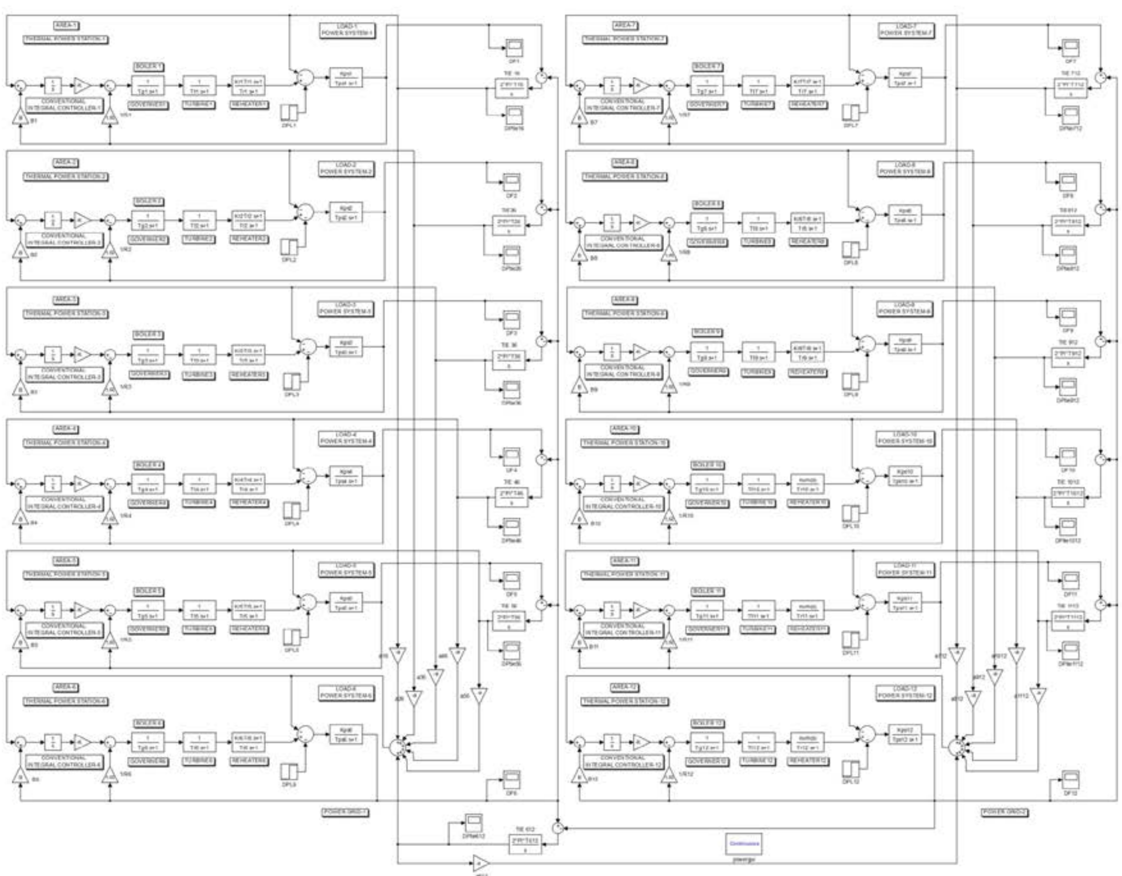

Fig.4 12-Area Two Interconnected Thermal Power Grid with Normal HVAC Tie-Line.

B. The SIMULINK MODEL of 12-Area Two Interconnected Thermal Power Grid with FACTS Tie-Line as shown in figure 5.

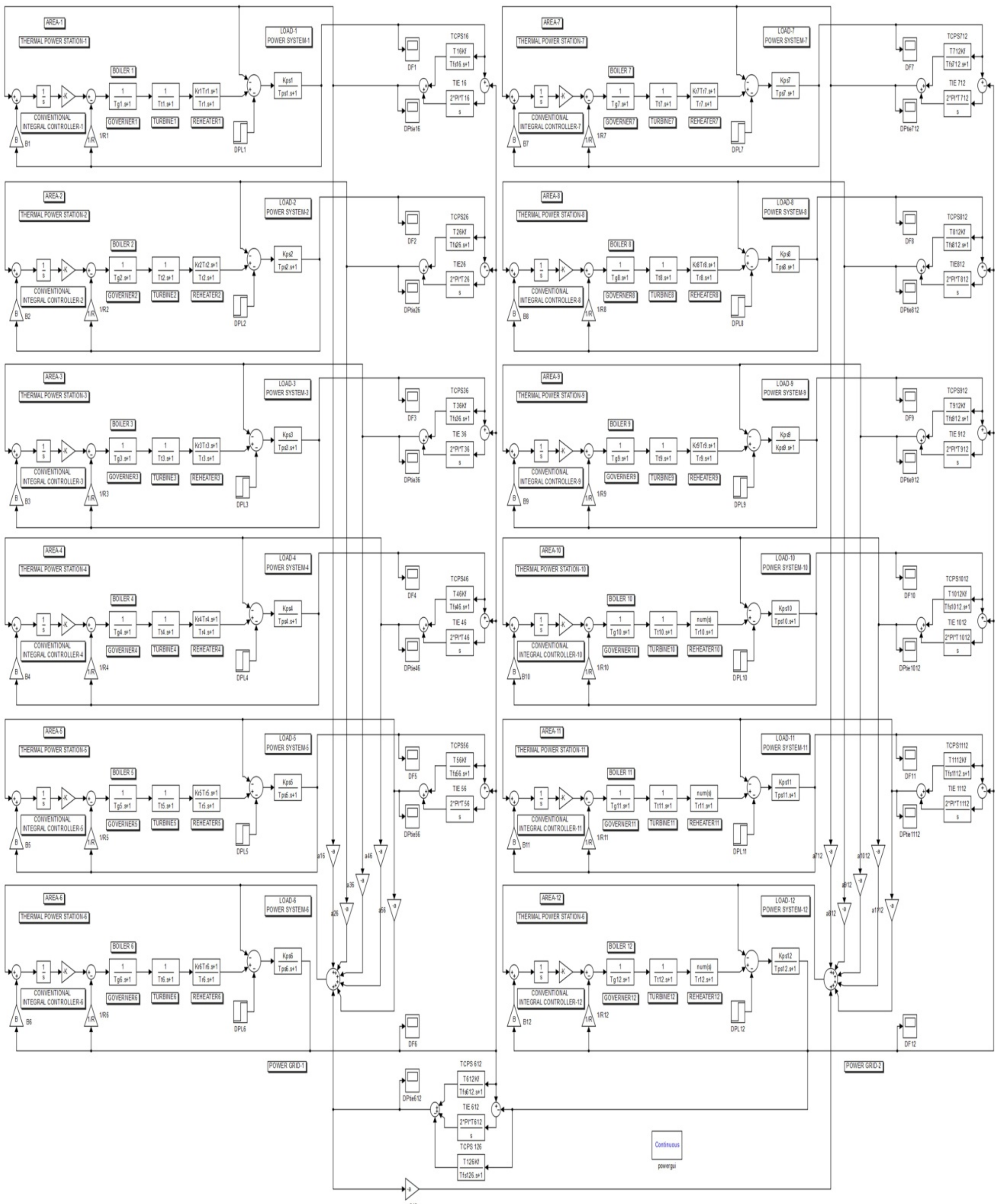

Fig.5 12-Area Two Interconnected Thermal Power Grid with FACTS Tie-Line.

C. The SIMULINK MODEL of 12-Area Two Interconnected Thermal Power Grid with HVAC-HVDC Parallel Tie-Line as shown in figure 6.

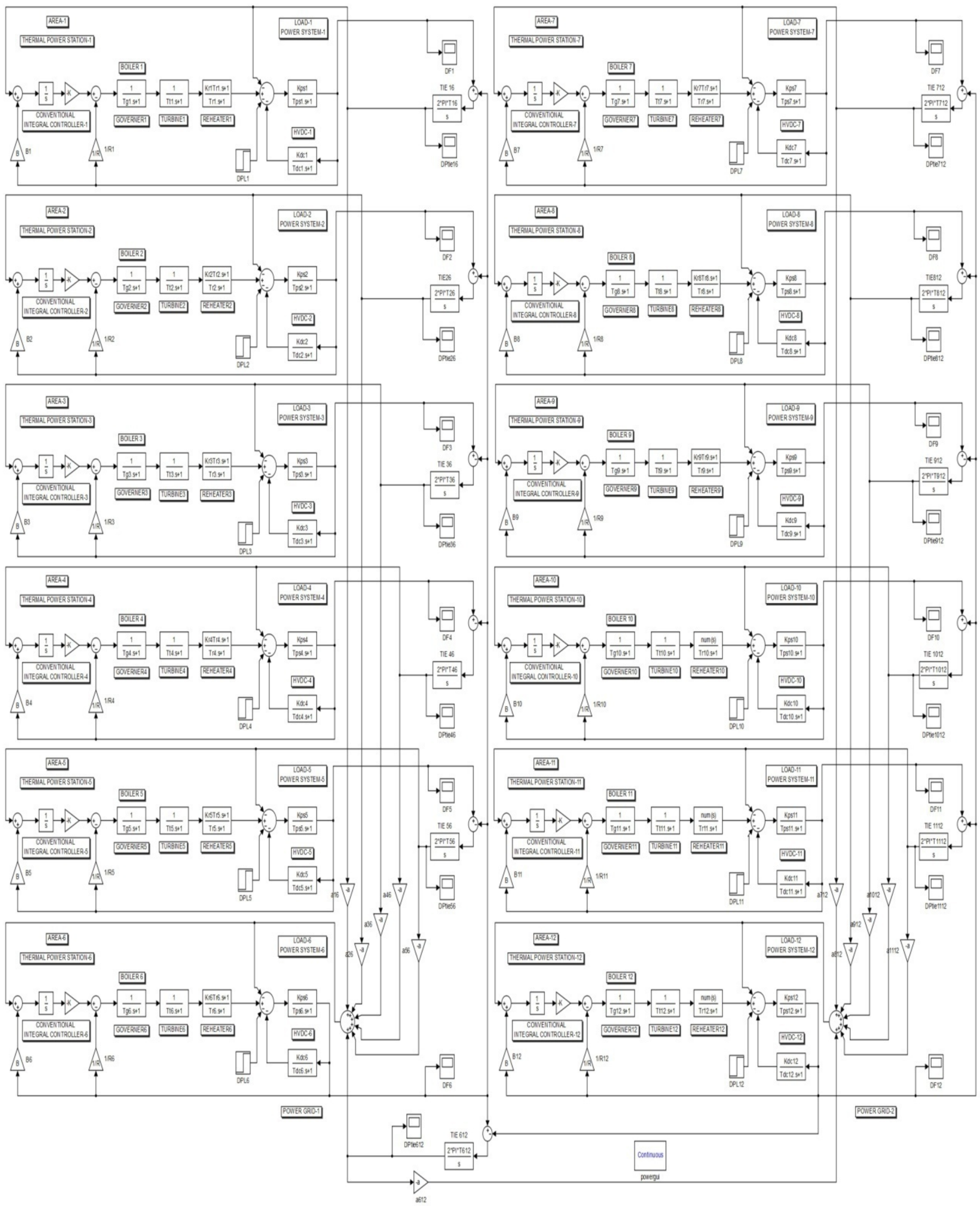

Fig.6 12-Area Two Interconnected Thermal Power Grid with HVAC-HVDC Parallel Tie-Line.

IV. MATLAB SIMULATION OUTPUT OF 12-AREA TWO INTERCONNECTED THERMAL POWER GRID WITH DIFFERENT TIE-LINE

The simulation is done in MATLAB Software-Math Works, Volume Version 8.1.0.604 (R2013a).

Before presentation of MATLAB SIMULATION OUTPUT of 12-Area Two Interconnected Thermal Power Grid with Different Tie-Line some definition are present below, this are important as output concern :

FD-PG-1: Frequency deviation of Power-Grid-1, FD-PG-1: [$\Delta F_6(s)$].

FD-PG-2: Frequency deviation of Power-Grid-2, FD-PG-1: [$\Delta F_{12}(s)$].

FDIG-PG-1: Frequency deviation of interconnected group of Power-Grid-1

FDIG-PG-1: [($\Delta F_1(s)$, $\Delta F_2(s)$, $\Delta F_3(s)$, $\Delta F_4(s)$, $\Delta F_5(s)$].

FDIG-PG-2: Frequency deviation of interconnected group of Power-Grid-2

FDIG-PG-2: [($\Delta F_7(s)$, $\Delta F_8(s)$, $\Delta F_9(s)$, $\Delta F_{10}(s)$, $\Delta F_{11}(s)$].

TPD-PG-1: Tie-line power deviation of Power-Grid-1

TPD-PG-1: [$\Delta P_{Tie16}(s)$, $\Delta P_{Tie26}(s)$, $\Delta P_{Tie36}(s)$, $\Delta P_{Tie46}(s)$, $\Delta P_{Tie56}(s)$].

TPD-PG-2: Tie-line power deviation of Power-Grid-2

TPD-PG-2: [$\Delta P_{Tie712}(s)$, $\Delta P_{Tie812}(s)$, $\Delta P_{Tie912}(s)$, $\Delta P_{Tie1012}(s)$, $\Delta P_{Tie1112}(s)$].

TPD-PG1&2: Tie-line power deviation between Power-Grid-1 to Power-Grid-2 [$\Delta P_{Tie612}(s)$].

A. The SIMULATION OUTPUT of 12-Area Two Interconnected Thermal Power Grid with Normal HVAC Tie-Line as shown in figure-(7), (8), (9), (10), (11).

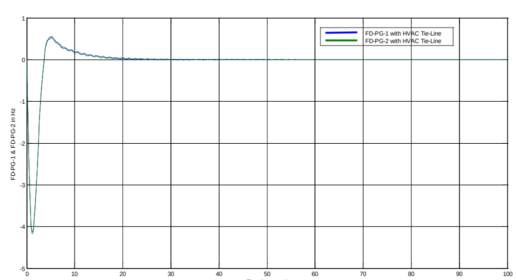

Fig.7 Waveform of FD-PG-1 & FD-PG-2 with normal HVAC tie-line.

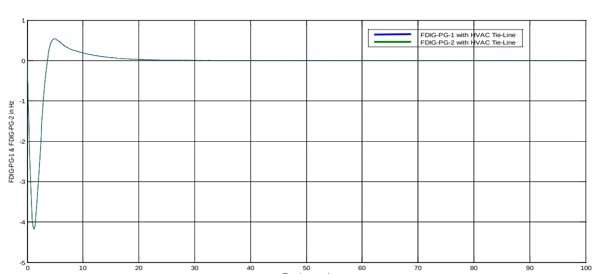

Fig.8 Waveform of FDIG-PG-1 & FDIG-PG-2 with normal HVAC tie-line.

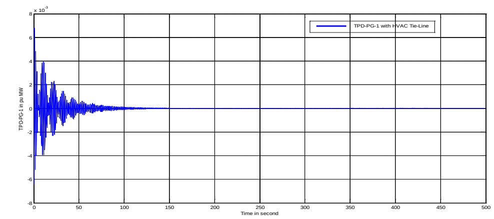

Fig.9 Waveform of TPD-PG-1 with normal HVAC tie-line.

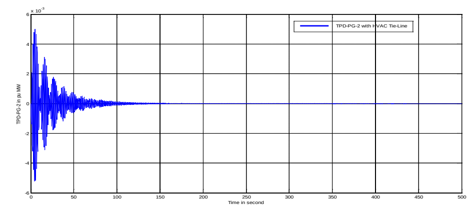

Fig.10 Waveform of TPD-PG-2 with normal HVAC tie-line.

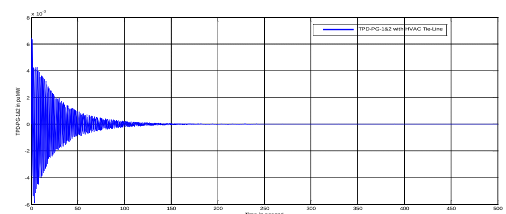

Fig.11 Waveform of TPD-PG-1&2 with normal HVAC tie-line.

B. The SIMULATION OUTPUT of 12-Area Two Interconnected Thermal Power Grid with FACTS Tie-Line as shown in figure-(12), (13), (14).

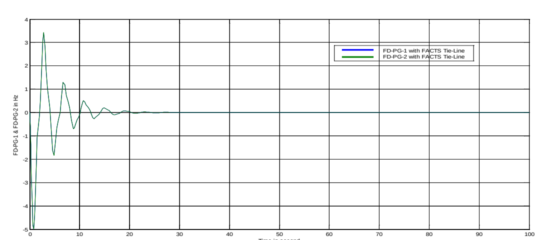

Fig.12 Waveform of FD-PG-1 & FD-PG-2 with FACTS tie-line.

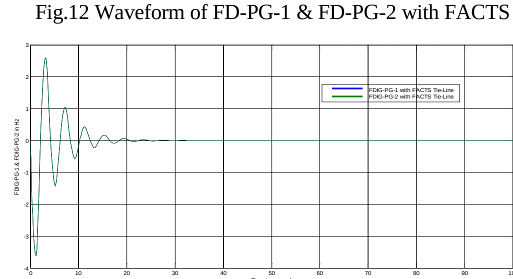

Fig.13 Waveform of FDIG-PG-1 & FDIG-PG-2 with FACTS tie-line.

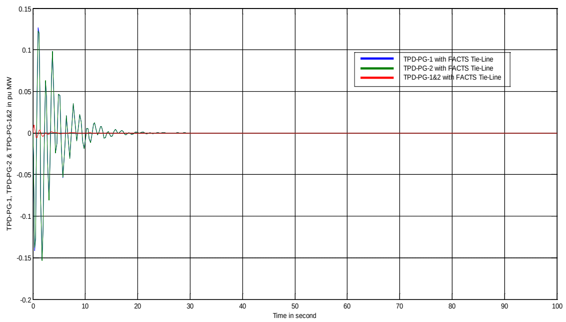

Fig.14 Waveform of TPD-PG-1, TPD-PG-2 and TPD-PG-1&2 with FACTS tie-line.

C. The SIMULATION OUTPUT of 12-Area Two Interconnected Thermal Power Grid with HVAC-HVDC Parallel Tie-Line as shown in figure 15& 16.

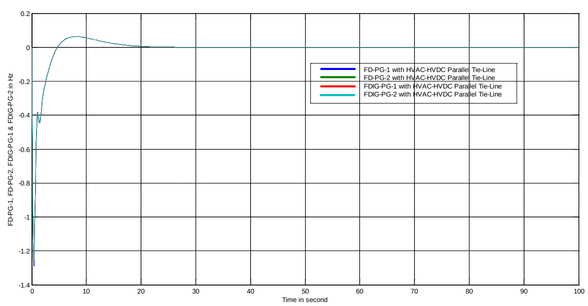

Fig.15 Waveform of FD-PG-1, FD-PG-2, FDIG-PG-1 & FDIG-PG-2 with HVAC-HVDC parallel tie-line.

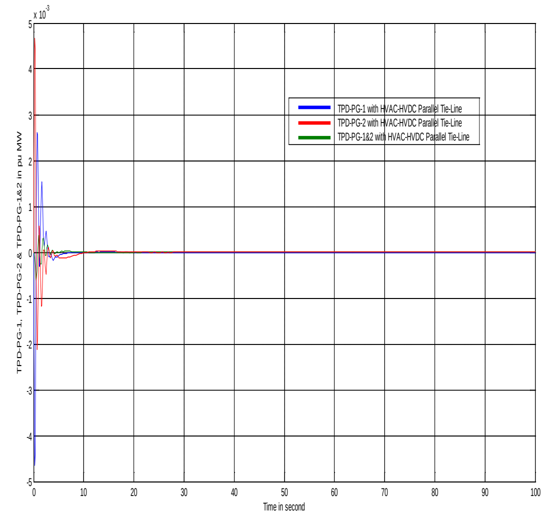

Fig.16 Waveform of TPD-PG-1,TPD-PG-2,TPD-PG-1&2 with HVAC-HVDC parallel tie-line.

V. MATLAB SIMULATION RESULT OF 12-AREA TWO INTERCONNECTED THERMAL POWER GRID WITH DIFFERENT TIE-LINE

The simulation is done in MATLAB Software-Math Works, Volume Version 8.1.0.604 (R2013a).

After load change in power grid-1 (area-6) (ΔP_{L6} = 0.01p.u.), 12-area two interconnected thermal power grid with its all 12 areas are synchronized at the same time (26.03 second) only in case of HVAC-HVDC parallel tie-line. Settling time of frequency and tie-line power deviation of 12-area two interconnected thermal power grid with different tie-line are presents in Table 1.

TABLE I SETTLING TIME OF FREQUENCY AND TIE-LINE POWER DEVIATION OF 12-AREA TWO INTERCONNECTED THERMAL POWER GRID WITH DIFFERENT TIE-LINE WHEN ΔP_{L6} = 0.01PU LOAD CHANGE IN POWER GRID-1 (CONTROL AREA-6).

Frequency and tie-line power deviation of Power-Grids	Settling time with normal HVAC Tie-Line (in sec)	Settling time with FACTS Tie-Line (in sec)	Settling time with HVAC-HVDC Parallel Tie-Line (in sec)
FD-PG-1	55.76 sec	27.74 sec	26.03 sec
FD-PG-2	59.81 sec	27.74 sec	26.03 sec
FDIG-PG-1	32.69 sec	32.43 sec	26.03 sec
FDIG-PG-2	31.23 sec	32.43 sec	26.03 sec
TPD-PG-1	429.9 sec With (+10%) tolerance	29.09 sec	11.02 sec
TPD-PG-2	429.9 sec	29.09 sec	20.00 sec
TPD-PG-1&2	244.5 sec	18.53 sec	20.82 sec

VI. CONCLUSION

1. In Synchronization (load frequency control) of 12-area two interconnected thermal power grid the HVAC-HVDC Parallel Tie-Line is showing batter power system dynamics performance as compare to the Flexible AC Transmission System (FACTS) Tie-Line and Normal HVAC Tie-Line.
2. Also the Flexible AC Transmission System (FACTS) Tie-Line is showing batter power system dynamics

performances as compare to the Normal HVAC Tie-Line.
3. Finally says the order for power system dynamics performance improvement by using different Tie-Line in case of load change is:

HVAC Tie-Line < FACTS Tie-Line < HVAC-HVDC Parallel Tie-Line.

REFERENCES

[1] P. Kundur, *Power System Stability and Control*, McGraw hill New York, 1994.

[2] F. Llewis and V. L. Syrmos "Optimal control," New Jersy, Englewood Cliffs, Prentice Hall, 1995.

[3] D. P. Kothari, I. J. Nagrath, *Modern Power System Analysis*, Tata McGraw Hill, Third Edition, 2003.

[4] D. P. Kothari and J. S. Dhillon *Power System Optimization*, Second Edition, New Delhi, India: Prentice Hall, 2010.

[5] Wadhwa C. L. 2007, *Electric Power System,* New Age International pub. 4th Edition.

[6] H. Bevrani and T. Hiyama, *Intelligent Automatic Generation Control.* New York, CRC Press Taylor and Francis, 2011.

[7] H. Bevrani, *Robust Power System Frequency Control.* New York: Springer, 2009.

[8] O. Elgerd, *Electric Energy System Theory:* an introduction, Second edition. New York: Mc Graw-Hill, 1983.

[9] Krishna Pal Singh Parmar "State space based load frequency control of multi-area power system" *PhD. Thesis, IIT Guwahati, India, October, 2013.*

[10] Control Toolbox, *MATLAB Software*-Math Works, Inc. MATLAB, Vol. Version 8.1.0.604 (R2013a).

[11] S. Mishra, G. Mallesham, and P. Sekhar, "Biogeography based optimal state feedback controller for frequency regulation of a smart microgrid," *IEEE Trans. on Smart Grid,* Vol. 4, No. 1, pp. 628-637, 2013.

[12] L. Xu and D. Chen, "Control and operation of a DC Microgrid with variable generation and energy storage", *IEEE Transaction on Power Delivery,* Vol. 26, No. 4, October 2011.

[13] K. P. Singh Parmar, S. Majhi, and D. P. Kothari, "Load frequency control of a realistic power system generation," *Int. J. of Elect Power and Energy Syst.,* Vol. 42, pp. 426-33, 2012.

[14] K. P. Singh Parmar, S. Majhi, and D. P. Kothari, "Improvement of dynamic performance of load frequency control of the two area power system," *Int. J. of Comp. App.,* Vol. 40, No. 10, pp. 28-32, Feb.2012.

[15] K. P. Singh Parmar, S. Majhi, and D. P. Kothari, "Load frequency control of an interconnected power system with thyristor controlled phase shifter in the tie-line," *Int. J. of Comp. App.,* Vol. 41, No. 9, pp. 27-30, 2012.

[16] K. P. Singh Parmar, S. Majhi and D. P. Kothari, "Multi-area load frequency control in a power system using optimal feedback method," *IEEE Conference Proceeding. PEDES 2010. New Delhi, India.*

[17] K. P. Singh Parmar, S. Majhi and D. P. Kothari, "Automatic generation control of an interconnected hydrothermal power system," *IEEE Conference Proceeding. INDICON 2010, Kolkata, India.*

[18] S. Ramesh and A. Krishnan, "Fuzzy rule based load frequency control in a parallel AC-DC interconnected power systems through HVDC link," *Int. J. of Comp. Appl.*, Vol. 1, No. 4, 2010.

[19] R. J. Abraham, D. Das, and A. Patra, "Damping oscillations in tie power and area frequency in a thermal power system with SMES-TCPS combination," *J. Elect. Syst.,* Vol. 7 No. 1, pp. 71-80, 2011.

[20] K. Subbaramaiah, V. C. J. Mohan, and V. C. V. Reddy, "Comparison of performance of SSSC and TCPS in automatic generation control of hydrothermal system under deregulated scenario," *Int. J. of Elec. and Comp. Eng.,* Vol. 1, No. 1, pp. 21-30, 2011.

[21] C. S. Rao, "Improvement of dynamic performance of AGC of hydrothermal system employing capacitive energy storage and TCPS," *Innov. Syst. Design and Eng.,* Vol. 2, No. 6, pp. 63-71, 2011.

[22] P. Bhatt, S. P. Ghoshal, R. Roy, and S. Ghosal, "Load frequency control of interconnected restructured power system along with DFIG and coordination operation of TCPS-SMES," *IEEE Conference Proceeding, PEDES, 2010.*

[23] K. Challa and P. N. Raw, "Analysis and design of controller for two area thermal-hydro-gas automatic generation control system," *IEEE Conference Proceeding, PEDES, 2010.*

[24] K. S. S. Ramakrishna, P. Sharma, and T.S. Bhatti, "AGC of interconnected power system with diverse sources of power generation," *Int. J. of Eng. Sci. and Tech*., Vol. 2, No. 5, pp. 51-65, 2010.

[25] J. Nanda, S. Mishra, and L.C. Saikia, "Maiden Application of Bacterial Foraging-Based Optimization Technique in Multi-Area Automatic Generation Control," *IEEE Transactions Power System*, Vol. 24, No. 2, pp. 602-609, 2009.