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Performance Analysis of Combined Application of FACTS and HVDC Parallel Tie-Line for Interconnection and Synchronization of Large Thermal Power Grid

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Abstract
This research work shows the working principle of two combined cases and application of flexible AC transmission system tie-line and high voltage direct current tie-line for interconnection and synchronization of two large thermal power grid system of 12 areas when load disturbance occurred in power grid-1 ΔP_{L6} = 0.01 pu. This research work is done with two interconnected linear, conventional and traditional thermal power grid system of 12 areas accepted reheater. Synchronization of thermal power grid system is done by two different cases of FACTS and HVDC parallel tie-line with the traditional integral controller in terms of settling time of frequency deviation of individual control areas and power grids and settling time of tie-line power deviation of individual control areas interconnected the power grids and two interconnected thermal power grids.

Keywords: *FACTS-HVDC parallel tie-line, FACTS tie-line, two interconnected linear, thermal power grid system, synchronization, traditional integral controller*

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INTRODUCTION
Designing a controller for very large power grid system is very difficult and complicated because programming for such system is very large. To overcome this problem two combined cases of FACTS tie-line and HVDC parallel tie-line are applied for interconnection and synchronization of two linear, conventional and traditional thermal power grids of 12 individual control areas with traditional integral controller.

Description of two interconnected thermal power grid system:
1. *Control Area-6 (Power Grid-1)*: Control area-6 is receiving power from its interconnected individual control areas (control area-1, control area-2, control area-3, control area-4, control area-5) and sending power for control area-12.
2. *Control Area-12 (Power Grid-2)*: Control area-12 is receiving power from control area-6 and its interconnected individual control areas (control area-7. Control area-8, control area-9, control area-10, control area-11).

The description of two combined cases of FACTS tie-line and HVDC parallel tie-line for interconnection and synchronization of two thermal power grid systems of 12 areas:
1. *Case-1*: FACTS-HVDC parallel tie-line is applied for interconnection of control area-6 and control area-12. In FACTS tie-line of FACTS-HVDC parallel tie-line two TCPS is applied in between control area-6 and control area-12 ends. For interconnection of individual control areas (control area-1, control area-2, control area-3, control area-4, control area-5, control area-7, control area-8, control area-9, control area-10, control area-11) to the respective control area-6(power grid-1) and control area-12(power grid-12) only one TCPS is applied in the individual control areas end. Case-1 as shown in Figure 1.
2. *Case-2:* FACTS tie-line is applied for interconnection of control area-6 and control area-12. In FACTS tie-line two TCPS is applied in between control area-6 and control area-12 ends. For interconnection of individual control areas (control area-1, control area-2, control

area-3, control area-4, control area-5, control area-7, control area-8, control area-9, control area-10, control area-11) to the respective control area-6 (power grid-1)and control area-12 (power grid-12) HVAC-HVDC parallel tie-line is applied. Case-2 as shown in Figure 2.

In FACTS tie-line of above two cases, TCPS is always applied in series with HVAC tie-line, so it is called FACTS tie-line.

Load change in control area-6 (power grid-1): $\Delta P_{L6} = 0.01$ pu.

K.P. Singh Parmar [2] is done in his research work, the compression between the performance of open loop feedback controller and closed loop feedback controller for load frequency control of multi-area multi-source power system with environment of HVAC tie-line, HVAC-HVDC parallel tie-line, flexible AC transmission system (FACTS) tie-line and deregulated environment. Operation and designing technique is easy for open loop feedback controller as compare to the closed loop feedback controller because less number of state variables is required for designing of open loop feedback controller as compare to the closed loop (full state) feedback controller. Full state feedback controller requires all the state variables of the power system in case of load variation in the power system, measurement of all state variables of the power system with accurate value in case of load variation in the power system is a tough task, so that the open loop feedback controller is batter as compare to the full state (closed loop) feedback controller.

Majority of research work is done by the power system researchers regarding the Load Frequency Control (LFC) or Automatic Generation Control (AGC) of interconnected power system considering with only HVAC tie-line with two or multi area power system. But present days as the load demand increasing researchers are required to focus on generation and transmission of huge amount of electrical power through FACTS and HVDC system efficiently, effectively and economically. HVDC link is operating in parallel with HVAC tie-line for improvement of power system dynamics performance of system in case of small disturbances with greater stability margins [5, 6]. And also other research work of load frequency control with HVAC-HVDC parallel tie-line is present in [2–10].

Flexibility require in any power system for its proper operation and control. Flexible AC transmission system (FACTS) device is connected in series with tie-line, for tie-line power flow control by its phase shifter angle of the FACTS device. Thyristor controlled phase shifter (TCPS) is an important FACTS device for improvement of power system dynamic performance in case any load change in interconnected power system. TCPS is connected in series with tie-line in the Load Frequency Control interconnected system and it is presents in [2, 8–14].

MATHEMATICAL MODEL OF TIE-LINE POWER EXCHANGE

12-Area Two Interconnected Thermal Power Grid with Case-1

The 12-area two interconnected thermal power grid with Case-1 as shown in Figure 1. In Case-1 for interconnection of two power grids, FACTS-HVDC parallel tie-line is applied.

1. In FACTS tie-line two TCPS is applied in series with HVAC tie-line between two power grids in each end of HVAC tie-line. 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 1.

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:

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

Where,

T_{612wps} = Synchronizing power coefficient without TCPS612

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

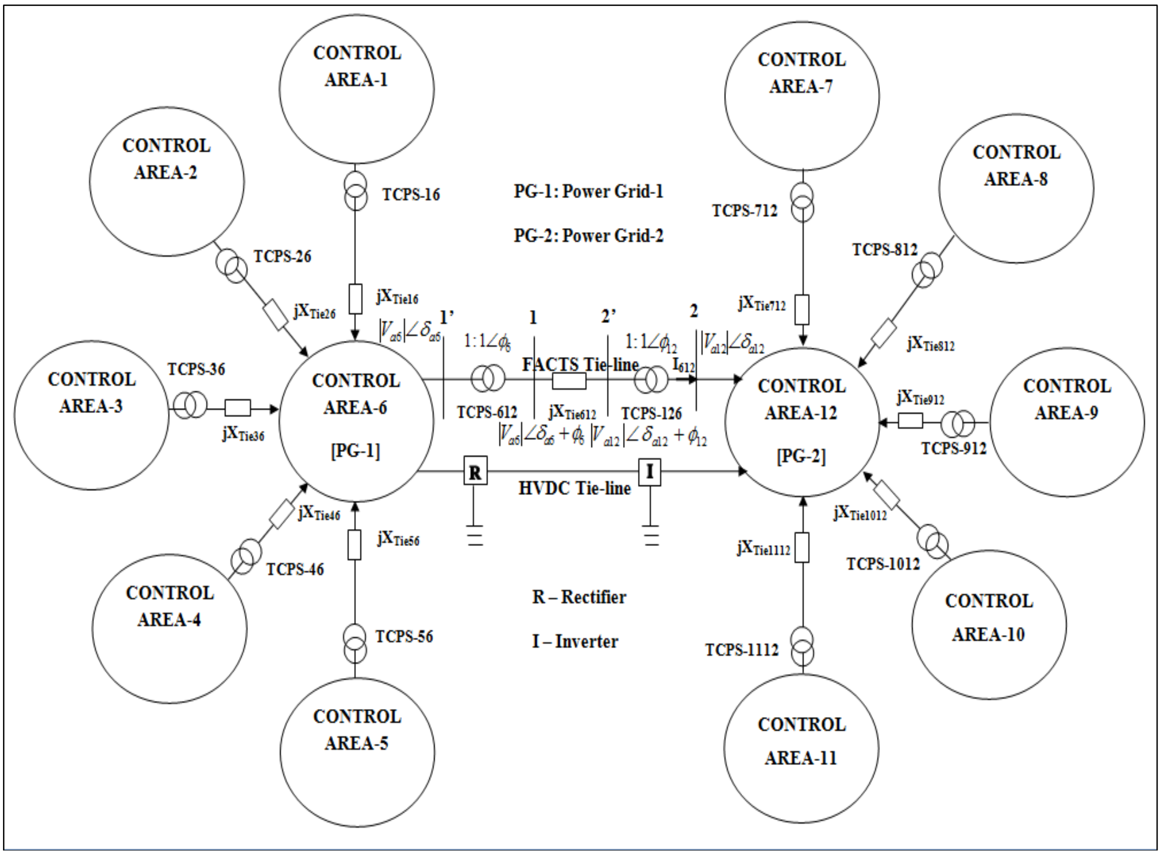

Fig. 1: 12-Area Two Interconnected Thermal Power Grid with Case-1.

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:

$$P_{TieFACTS612} - jQ_{TieFACTS612} = (V_{ar6})^* I_{612} = [|V_{ar6}|\angle-(\delta_{ar6}+\phi_6)]\, I_{612}$$

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

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

The real part of the above equation $P_{TieFACTS612}$

$$= \frac{|V_{ar6}|\ |V_{ar12}|}{X_{tie612}}\mathrm{Sin}(\delta_{ar6} - \delta_{ar12} + \phi_6)$$

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

$$\Delta P_{TieFACTS612} = \frac{|V_{ar6}|\ |V_{ar12}|}{X_{tie612}}\mathrm{Cos}(\delta^\circ_{ar6} - \delta^\circ_{ar12} + \phi^\circ_6) * \mathrm{Sin}(\Delta\delta_{ar6} - \Delta\delta_{ar12} + \Delta\phi_6)$$

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

$$\Delta P_{TieFACTS612} = \frac{|V_{ar6}|\ |V_{ar12}|}{X_{tie612}}\mathrm{Cos}(\delta^\circ_{ar6} - \delta^\circ_{ar12} + \phi^\circ_6) * (\Delta\delta_{ar6} - \Delta\delta_{ar12} + \Delta\phi_6)$$

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

So that $\Delta P_{TieFACTS612} = T_{612}(\Delta\delta_{ar6} - \Delta\delta_{ar12} + \Delta\phi_6) = T_{612}(\Delta\delta_{ar6} - \Delta\delta_{ar12}) + T_{612}\Delta\phi_6$

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

$$\Delta P_{TieFACTS612} = T_{612}\left(2\pi\int_0^t \Delta F_6\,dt - 2\pi\int_0^t \Delta F_{12}\,dt\right) + T_{612}\Delta\phi_6$$

Taking Laplace transforms of above equation $\Delta P_{TieFACTS612}(s) = \frac{2\pi T_{612}}{s}[\Delta F_6(s) - \Delta F_{12}(s)] + T_{612}\Delta\phi_6(s)$

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

$\Delta P_{TieFACTS612}(s) = \frac{2\pi T_{612}}{s}[\Delta F_6(s) - \Delta F_{12}(s)] + T_{612}\Delta\phi_6(s) - T_{126}\,\Delta\phi_{12}(s)$ (1)

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

$$\Delta\phi_6(s) = \frac{K_{\phi 6}}{1+sT_{\phi 6}}\,\Delta Error(s) = \frac{K_{\phi 6}}{1+sT_{\phi 6}}\,\Delta F_6(s)$$

Where, $K_{\phi 6}$ = Gain and $T_{\phi 6}$ = Time constant of TCPS612

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

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

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

Where, $K_{\phi 12}$ = Gain and $T_{\phi 12}$ = Time constant of TCPS126

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

Also,

$\Delta P_{TieFACTS1}(s) = \Delta P_{TieFACTS16}(s) = \frac{2\pi T_{16}}{s}[\Delta F_1(s) - \Delta F_6(s)] + T_{16}\,\Delta\phi_1(s)$,

$\Delta P_{TieFACTS2}(s) = \Delta P_{TieFACTS26}(s) = \frac{2\pi T_{26}}{s}[\Delta F_2(s) - \Delta F_6(s)] + T_{26}\,\Delta\phi_2(s)$,

$\Delta P_{TieFACTS3}(s) = \Delta P_{TieFACTS36}(s) = \frac{2\pi T_{36}}{s}[\Delta F_3(s) - \Delta F_6(s)] + T_{36}\,\Delta\phi_3(s)$,

$\Delta P_{TieFACTS4}(s) = \Delta P_{TieFACTS46}(s) = \frac{2\pi T_{46}}{s}[\Delta F_4(s) - \Delta F_6(s)] + T_{46}\,\Delta\phi_4(s)$,

$\Delta P_{TieFACTS5}(s) = \Delta P_{TieFACTS56}(s) = \frac{2\pi T_{56}}{s}[\Delta F_5(s) - \Delta F_6(s)] + T_{56}\,\Delta\phi_5(s)$,

$\Delta P_{TieFACTS7}(s) = \Delta P_{TieFACTS712}(s) = \frac{2\pi T_{712}}{s}[\Delta F_7(s) - \Delta F_{12}(s)] + T_{712}\,\Delta\phi_7(s)$,

$\Delta P_{TieFACTS8}(s) = \Delta P_{TieFACTS812}(s) = \frac{2\pi T_{812}}{s}[\Delta F_8(s) - \Delta F_{12}(s)] + T_{812}\,\Delta\phi_8(s)$,

$\Delta P_{TieFACTS9}(s) = \Delta P_{TieFACTS912}(s) = \frac{2\pi T_{912}}{s}[\Delta F_9(s) - \Delta F_{12}(s)] + T_{912}\,\Delta\phi_9(s)$,

$\Delta P_{TieFACTS10}(s) = \Delta P_{TieFACTS1012}(s) = \frac{2\pi T_{1012}}{s}[\Delta F_{10}(s) - \Delta F_{12}(s)] + T_{1012}\,\Delta\phi_{10}(s)$,

$\Delta P_{TieFACTS11}(s) = \Delta P_{TieFACTS1112}(s) = \frac{2\pi T_{1112}}{s}[\Delta F_{11}(s) - \Delta F_{12}(s)] + T_{1112}\,\Delta\phi_{11}(s)$.

Power Transfer from Power Grid-1 to Power Grid-2 through HVDC LINK

$$\Delta P_{TieDC6}(s) = \Delta P_{TieDC612}(s) = \frac{K_{DC6}}{s\,T_{DC6}+1}[\Delta F_6(s) - \Delta F_{12}(s)]$$

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

$\Delta P_{Tie6}(s) = \Delta P_{TieFACTS6}(s) + \Delta P_{TieDC6}(s)$ (2)

$\Delta P_{TieFACTS6}(s) = a_{16}\,\Delta P_{TieFACTS1}(s) + a_{26}\,\Delta P_{TieFACTS2}(s) + a_{36}\,\Delta P_{TieFACTS3}(s) + a_{46}\,\Delta P_{TieFACTS4}(s) + a_{56}\,\Delta P_{TieFACTS5}(s) + \Delta P_{TieFACTS612}(s)$

[Here, $\Delta P_{TieFACTS612}(s) \neq \Delta P_{TieFACTS6}(s)$]

$= a_{16}\,\Delta P_{TieFACTS16}(s) + a_{26}\,\Delta P_{TieFACTS26}(s) + a_{36}\,\Delta P_{TieFACTS36}(s) + a_{46}\,\Delta P_{TieFACTS46}(s) + a_{56}\,\Delta P_{TieFACTS56}(s) + \Delta P_{TieFACTS612}(s)$

$= \frac{2\pi}{s}[\sum_{i=1,2,3,4,5} a_{i6}T_{i6}\Delta F_i(s) - \sum_{i=1,2,3,4,5} a_{i6}T_{i6}\,\Delta F_6(s)] + \sum_{i=1,2,3,4,5} a_{i6}T_{i6}\,\Delta\phi_i(s) + \Delta P_{TieFACTS612}(s)$

$= a_{16}[\frac{2\pi T_{16}}{s}\{\Delta F_1(s) - \Delta F_6(s)\} + T_{16}\Delta\phi_1(s)] + a_{26}[\frac{2\pi T_{26}}{s}\{\Delta F_2(s) - \Delta F_6(s)\} + T_{26}\Delta\phi_2(s)] + a_{36}[\frac{2\pi T_{36}}{s}\{\Delta F_3(s) - \Delta F_6(s)\} + T_{36}\Delta\phi_3(s)] + a_{46}[\frac{2\pi T_{46}}{s}\{\Delta F_4(s) - \Delta F_6(s)\} + T_{46}\Delta\phi_4(s)] + a_{56}[\frac{2\pi T_{56}}{s}\{\Delta F_5(s) - \Delta F_6(s)\} + T_{56}\Delta\phi_5(s)] + [\frac{2\pi T_{612}}{s}\{\Delta F_6(s) - \Delta F_{12}(s)\} + T_{612}\Delta\phi_6(s) - T_{126}\Delta\phi_{12}(s)]$ (3)

$\Delta P_{TieDC6}(s) = \Delta P_{TieDC612}(s) = \frac{K_{DC6}}{s\,T_{DC6}+1}[\Delta F_6(s) - \Delta F_{12}(s)]$ (4)

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

$\Delta P_{Tie12}(s) = \Delta P_{TieFACTS12}(s) + \Delta P_{TieDC12}(s)$ (5)

$\Delta P_{TieFACTS12}(s) = a_{612}\,\Delta P_{TieFACTS612}(s) + a_{712}\,\Delta P_{TieFACTS7}(s) + a_{812}\,\Delta P_{TieFACTS8}(s) + a_{912}\,\Delta P_{TieFACTS9}(s) + a_{1012}\,\Delta P_{TieFACTS10}(s) + a_{1112}\,\Delta P_{TieFACTS11}(s)$

[Here, $\Delta P_{TieFACTS612}(s) \neq \Delta P_{TieFACTS6}(s)$]

$= a_{612}\,\Delta P_{TieFACTS612}(s) + a_{712}\,\Delta P_{TieFACTS712}(s) + a_{812}\,\Delta P_{TieFACTS812}(s) + a_{912}\,\Delta P_{TieFACTS912}(s) + a_{1012}\Delta P_{TieFACTS1012}(s) + a_{1112}\,\Delta P_{TieFACTS1112}(s)$

$= a_{612}\,\Delta P_{TieFACTS612}(s) + \frac{2\pi}{s}[\sum_{k=7,8,9,10,11} a_{k12}T_{k12}\Delta F_k(s) - \sum_{k=7,8,9,10,11} a_{k12}T_{k12}\Delta F_{12}(s)] + \sum_{k=7,8,9,10,11} a_{k12}T_{k12}\,\Delta\phi_k(s)$

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$= a_{612}\, [\frac{2\,\pi\, T_{612}}{s}\, \{\Delta F_6(s) - \Delta F_{12}(s)\} + T_{612}\, \Delta\phi_6(s) - T_{126}\, \Delta\phi_{12}(s)] + a_{712}\, [\frac{2\,\pi\, T_{712}}{s}\, \{\Delta F_7(s) - \Delta F_{12}(s)\} + T_{712}\, \Delta\phi_7(s)] + a_{812}\, [\frac{2\,\pi\, T_{812}}{s}\, \{\Delta F_8(s) - \Delta F_{12}(s)\} + T_{812}\, \Delta\phi_8(s)] + a_{912}\, [\frac{2\,\pi\, T_{912}}{s}\, \{\Delta F_9(s) - \Delta F_{12}(s)\} + T_{912}\, \Delta\phi_9(s)] + a_{1012}\, [\frac{2[T_{1012}}{s}\, \{\Delta F_{10}(s) - \Delta F_{12}(s)\} + T_{1012}\, \Delta\phi_{10}(s)] + a_{1112}\, [\frac{2[T_{1112}}{s}\, \{\Delta F_{11}(s) - \Delta F_{12}(s)\} + T_{1112}\, \Delta\phi_{11}(s)]$ (6)

$\Delta P_{TieDC12}(s) = a_{612}\, \Delta P_{TieDC6}(s) = a_{612}\, \Delta P_{TieDC612}(s) = \frac{a_{612}\, K_{DC6}}{s\, T_{DC6} + 1}\, [\Delta F_6(s) - \Delta F_{12}(s)]$ (7)

Area control error for area-1 with FACTS tie-line, $ACE_1(s) = B_1\, \Delta F_1(s) + \Delta P_{TieFACTS1}(s)$
Area control error for area-2 with FACTS tie-line, $ACE_2(s) = B_2\, \Delta F_2(s) + \Delta P_{TieFACTS2}(s)$
Area control error for area-3 with FACTS tie-line, $ACE_3(s) = B_3\, \Delta F_3(s) + \Delta P_{TieFACTS3}(s)$
Area control error for area-4 with FACTS tie-line, $ACE_4(s) = B_4\, \Delta F_4(s) + \Delta P_{TieFACTS4}(s)$
Area control error for area-5 with FACTS tie-line, $ACE_5(s) = B_5\, \Delta F_5(s) + \Delta P_{TieFACTS5}(s)$
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, $ACE_7(s) = B_7\, \Delta F_7(s) + \Delta P_{TieFACTS7}(s)$
Area control error for area-8 with FACTS tie-line, $ACE_8(s) = B_8\, \Delta F_8(s) + \Delta P_{TieFACTS8}(s)$
Area control error for area-9 with FACTS tie-line, $ACE_9(s) = B_9\, \Delta F_9(s) + \Delta P_{TieFACTS9}(s)$
Area control error for area-10 with FACTS tie-line, $ACE_{10}(s) = B_{10}\, \Delta F_{10}(s) + \Delta P_{TieFACTS10}(s)$
Area control error for area-11 with FACTS tie-line, $ACE_{11}(s) = B_{11}\, \Delta F_{11}(s) + \Delta P_{TieFACTS11}(s)$
Area control error for area-12 (power grid-2) with FACTS tie-line, $ACE_{12}(s) = B_{12}\, \Delta F_{12}(s) + \Delta P_{Tie12}(s)$.

12-Area Two Interconnected Thermal Power Grid with Case-2

The 12-area two interconnected thermal power grid with Case-1 as shown in Figure 2.

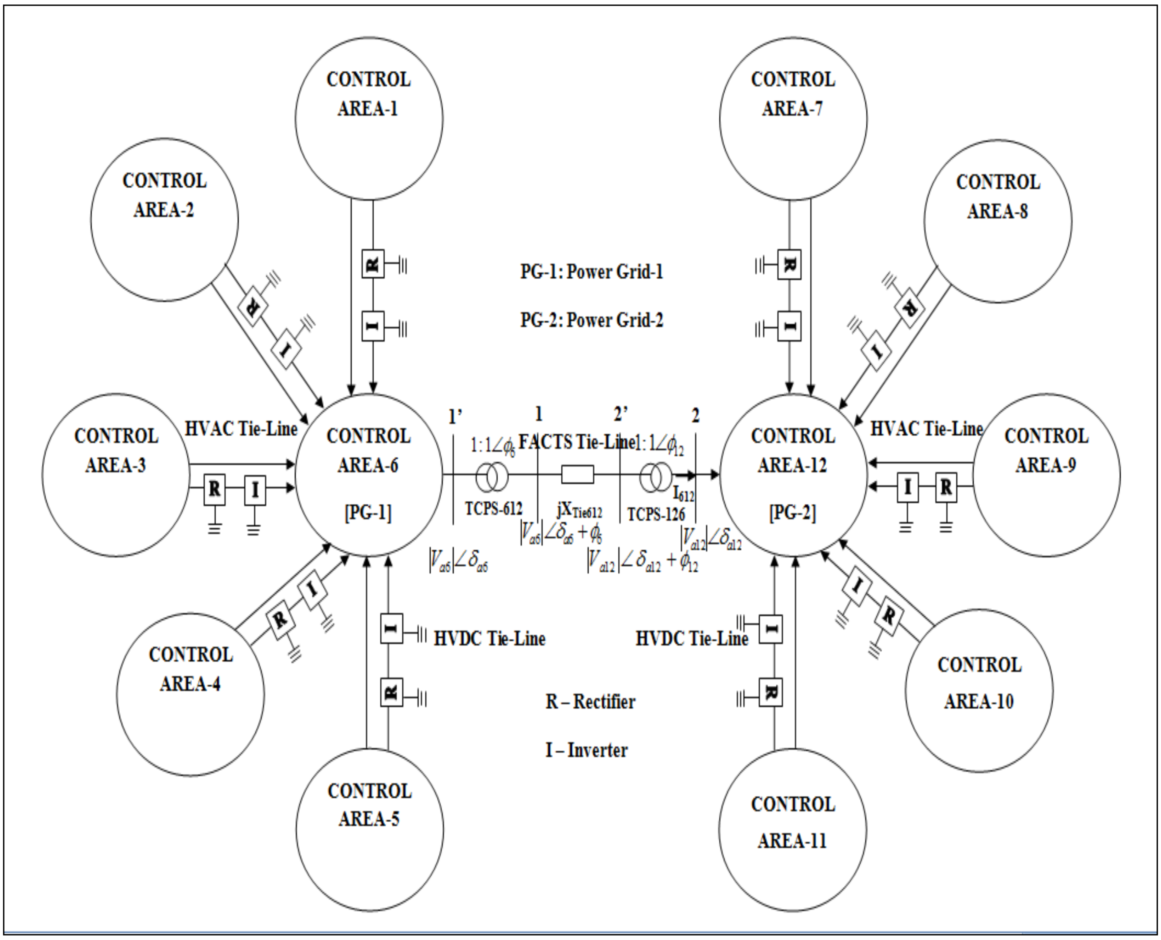

Fig. 2: *12-Area Two Interconnected Thermal Power Grid with Case-2.*

In Case-2, for interconnection of two power grids, FACTS tie-line is applied. In FACTS tie-line two TCPS is applied in series with HVAC tie-line between two power grids in each end of HVAC tie-line.

Power transfer from Power Grid-1 to Power Grid-2 through FACTS tie-line: From equation no. (1)

$$\Delta P_{TieFACTS612}(s) = \frac{2sT_{612}}{s}[\Delta F_6(s) - \Delta F_{12}(s)] + T_{612}\Delta\phi_6(s) - T_{126}\,\Delta\phi_{12}(s)$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\Delta P_{Tie6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s) \qquad (8)$$

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

$$\Delta P_{TieAC6}(s) = a_{16}\,\Delta P_{TieAC1}(s) + a_{26}\,\Delta P_{TieAC2}(s) + a_{36}\,\Delta P_{TieAC3}(s) + a_{46}\,\Delta P_{TieAC4}(s) + a_{56}\,\Delta P_{TieAC5}(s) + \Delta P_{TieFACTS612}(s)$$

[Here $\Delta P_{TieFACTS612}(s) \neq \Delta P_{TieAC6}(s)$]

$$= a_{16}\,\Delta P_{TieAC16}(s) + a_{26}\,\Delta P_{TieAC26}(s) + a_{36}\,\Delta P_{TieAC36}(s) + a_{46}\,\Delta P_{TieAC46}(s) + a_{56}\,\Delta P_{TieAC56}(s) + \Delta P_{TieFACTS612}(s)$$

$$= \frac{2}{s}\Big[\sum_{i=1,2,3,4,5} a_{i6}T_{i6}\Delta F_i(s) - \sum_{i=1,2,3,4,5} a_{i6}T_{i6}\,\Delta F_6(s)\Big] + \Delta P_{TieFACTS612}(s)$$

$= \frac{2\,a_{16}T_{16}}{s}[\Delta F_1(s) - \Delta F_6(s)] + \frac{2sa_{26}T_{26}}{s}[\Delta F_2(s) - \Delta F_6(s)] + \frac{2sa_{36}T_{36}}{s}[\Delta F_3(s) - \Delta F_6(s)] + \frac{2\,a_{46}T_{46}}{s}[\Delta F_4(s) - \Delta F_6(s)] + \frac{2sa_{56}T_{56}}{s}[\Delta F_5(s) - \Delta F_6(s)] + \frac{2sT_{612}}{s}[\Delta F_6(s) - \Delta F_{12}(s)] + T_{612}\Delta\phi_6(s) - T_{126}\Delta\phi_{12}(s)$ (9)

$\Delta P_{TieDC6}(s) = a_{16}\Delta P_{TieDC1}(s) + a_{26}\Delta P_{TieDC2}(s) + a_{36}\Delta P_{TieDC3}(s) + a_{46}\Delta P_{TieDC4}(s) + a_{56}\Delta P_{TieDC5}(s) + \{\Delta P_{TieDC612}(s) = 0\}$
[Here $\Delta P_{TieDC612}(s) \neq \Delta P_{TieDC6}(s)$, Also $\{\Delta P_{TieDC612}(s) = 0\}$]
$= a_{16}\Delta P_{TieDC16}(s) + a_{26}\Delta P_{TieDC26}(s) + a_{36}\Delta P_{TieDC36}(s) + a_{46}\Delta P_{TieDC46}(s) + a_{56}\Delta P_{TieDC56}(s)$
$= \frac{a_{16}K_{DC1}}{sT_{DC1}+1}[\Delta F_1(s) - \Delta F_6(s)] + \frac{a_{26}K_{DC2}}{sT_{DC2}+1}[\Delta F_2(s) - \Delta F_6(s)] + \frac{a_{36}K_{DC3}}{sT_{DC3}+1}[\Delta F_3(s) - \Delta F_6(s)] + \frac{a_{46}K_{DC4}}{sT_{DC4}+1}[\Delta F_4(s) - \Delta F_6(s)] + \frac{a_{56}K_{DC5}}{sT_{DC5}+1}[\Delta F_5(s) - \Delta F_6(s)]$ (10)

The tie-line power equation of power grid -2 (control area-12) is $\Delta P_{Tie12}(s)$, then:
$\Delta P_{Tie12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s)$ (11)

Where, $\Delta P_{TieAC12}(s)$ and $\Delta P_{TieDC12}(s)$ are,
$\Delta P_{TieAC12}(s) = a_{612}\Delta P_{TieFACTS612}(s) + a_{712}\Delta P_{TieAC7}(s) + a_{812}\Delta P_{TieAC8}(s) + a_{912}\Delta P_{TieAC9}(s) + a_{1012}\Delta P_{TieAC10}(s) + a_{1112}\Delta P_{TieAC11}(s)$
[Here $\Delta P_{TieFACTS612}(s) \neq \Delta P_{TieAC6}(s)$]
$= a_{612}\Delta P_{TieFACTS612}(s) + a_{712}\Delta P_{TieAC712}(s) + a_{812}\Delta P_{TieAC812}(s) + a_{912}\Delta P_{TieAC912}(s) + a_{1012}\Delta P_{TieAC1012}(s) + a_{1112}\Delta P_{TieAC1112}(s)$
$= a_{612}\Delta P_{TieFACTS612}(s) + \frac{2s}{s}[\sum_{k=7,8,9,10,11} a_{k12}T_{k12}\Delta F_k(s) - \sum_{k=7,8,9,10,11} a_{k12}T_{k12}\Delta F_{12}(s)]$
$= \frac{2\,a_{612}T_{612}}{s}[\Delta F_6(s) - \Delta F_{12}(s)] + T_{612}\Delta\phi_6(s) - T_{126}\Delta\phi_{12}(s) + \frac{2sa_{712}T_{712}}{s}[\Delta F_7(s) - \Delta F_{12}(s)] + \frac{2\,a_{812}T_{812}}{s}[\Delta F_8(s) - \Delta F_{12}(s)] + \frac{2sa_{912}T_{912}}{s}[\Delta F_9(s) - \Delta F_{12}(s)] + \frac{2\,a_{1012}T_{1012}}{s}[\Delta F_{10}(s) - \Delta F_{12}(s)] + \frac{2sa_{1112}T_{1112}}{s}[\Delta F_{11}(s) - \Delta F_{12}(s)]$ (12)

$\Delta P_{TieDC12}(s) = a_{612}\{\Delta P_{TieDC612}(s) = 0\} + a_{712}\Delta P_{TieDC7}(s) + a_{812}\Delta P_{TieDC8}(s) + a_{912}\Delta P_{TieDC9}(s) + a_{1012}\Delta P_{TieDC10}(s) + a_{1112}\Delta P_{TieDC11}(s)$
[Here $\Delta P_{TieDC612}(s) \neq \Delta P_{TieDC6}(s)$, $\{\Delta P_{TieDC612}(s) = 0\}$]
$= a_{712}\Delta P_{TieDC712}(s) + a_{812}\Delta P_{TieDC812}(s) + a_{912}\Delta P_{TieDC912}(s) + a_{1012}\Delta P_{TieDC1012}(s) + a_{1112}\Delta P_{TieDC1112}(s)$
$= \frac{a_{712}K_{DC7}}{sT_{DC7}+1}[\Delta F_7(s) - \Delta F_{12}(s)] + \frac{a_{812}K_{DC8}}{sT_{DC8}+1}[\Delta F_8(s) - \Delta F_{12}(s)] + \frac{a_{912}K_{DC9}}{sT_{DC9}+1}[\Delta F_9(s) - \Delta F_{12}(s)] + \frac{a_{1012}K_{DC10}}{sT_{DC10}+1}[\Delta F_{10}(s) - \Delta F_{12}(s)] + \frac{a_{1112}K_{DC11}}{sT_{DC11}+1}[\Delta F_{11}(s) - \Delta F_{12}(s)]$ (13)

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

12-Area Two Interconnected Thermal Power Grid Parameters with Case-1 AND Case-2

The transfer function of various blocks in 12-area two interconnected thermal power grid with Case-1 and Case-2:

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 re-heater $P_{RT\,(i)}(s) = \frac{s\,K_{R(i)}T_{R(i)}+1}{s\,T_{R(i)}+1}$

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 Controlled Phase Shifters is: $TCPS612 = T_{612}\frac{K_{\phi 6}}{1+sT_{\phi 6}}$ and $TCPS126 = T_{126}\frac{K_{\phi 12}}{1+sT_{\phi 12}}$

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 and Base MVA = 2000 MVA
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 = 0.0868 puMW/radian
Bias constants B = 0.425 puMW/Hz,
Speed regulation of governors R = 2.4 Hz/puMW
Frequency of power system = 60 Hz,
Power system gain constants K_{PS} = 120 Hz/puMW
Power system time constants T_{PS} = 20 sec,
Turbine time constants T_t = 0.3 sec,
Re-heater gain constants K_R = 0.5 sec and and Re-heater turbine time constants T_R = 10 sec.
HVDC-Link: Gain K_{DC} = 1, Time constants T_{DC} = 0.2 sec and Capacity of HVDC-Link = 20 MW
TCPS: Gain K_{ϕ} = 1.5 rad/Hz and Time constants T_{ϕ} = 0.1 sec
Phase shifter angle of TCPS: $\phi_{MAX} = 10°$ and $\phi_{MIN} = -10°$
Load change in power grid-1: ΔP_{L6} = 0.01 pu

Value of integral control gain in Case-1:
$K_1 = K_2 = K_3 = K_4 = K_5 = K_7 = K_8 = K_9 = K_{10} = K_{11} = 1.35$ and $K_6 = K_{12} = 1.5$

Value of integral control gain in Case-2:
$K_1 = K_2 = K_3 = K_4 = K_5 = K_7 = K_8 = K_9 = K_{10} = K_{11} = 2.35$ and $K_6 = K_{12} = 1.1$.

(1) Tie-Line Power Calculation with Case-1

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, and area-5) and sending 200

MW power for power grid-2. We know $\Delta P_{Tie6}(s)$ is:
$\Delta P_{Tie6}(s) = \Delta P_{TieFACTS6}(s) + \Delta P_{TieDC6}(s)$

Where, $\Delta P_{TieFACTS6}(s)$ and $\Delta P_{TieDC6}(s)$ are,
$\Delta P_{TieFACTS6}(s) = a_{16}\,\Delta P_{TieFACTS16}(s) + a_{26}\,\Delta P_{TieFACTS26}(s) + a_{36}\,\Delta P_{TieFACTS36}(s) + a_{46}\,\Delta P_{TieFACTS46}(s) + a_{56}\,\Delta P_{TieFACTS56}(s) + \Delta P_{TieFACTS612}(s)$
= [(-1) 200 + (-1) 200 + (-1) 200 + (-1) 200 + (-1) 200 + {180}]
= [(-1000) + {180}] = -820 MW

$\Delta P_{TieDC6}(s) = \Delta P_{TieDC612}(s) = 20$ MW
$\Delta P_{Tie6}(s) = \Delta P_{TieFACTS6}(s) + \Delta P_{TieDC6}(s)$ = [(-1000) + {180} + {20}] = [(-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:
$\Delta P_{Tie12}(s) = \Delta P_{TieFACTS12}(s) + \Delta P_{TieDC12}(s)$

Where, $\Delta P_{TieFACTS12}(s)$ and $\Delta P_{TieDC12}(s)$ are,
$\Delta P_{TieFACTS12}(s) = a_{612}\,\Delta P_{TieFACTS612}(s) + a_{712}\,\Delta P_{TieFACTS712}(s) + a_{812}\,\Delta P_{TieFACTS812}(s) + a_{912}\,\Delta P_{TieFACTS912}(s) + a_{1012}\Delta P_{TieFACTS1012}(s) + a_{1112}\,\Delta P_{TieFACTS1112}(s)$
= [{(-1) 180} + (-1) 200 + (-1) 200 + (-1) 200 + (-1) 200 + (-1) 200]
= [{-180} + (-1000)] = -1180 MW

$\Delta P_{TieDC12}(s) = a_{612}\,\Delta P_{TieDC6}(s) = a_{612}\,\Delta P_{TieDC612}(s)$ = (-1) 20 = -20 MW

$\Delta P_{Tie12}(s) = \Delta P_{TieFACTS12}(s) + \Delta P_{TieDC12}(s)$ = [{-180} + (-1000) + {-20}] = [{-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 Case-2
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,
$\Delta P_{TieAC6}(s) = a_{16}\,\Delta P_{TieAC16}(s) + a_{26}\,\Delta P_{TieAC26}(s) + a_{36}\,\Delta P_{TieAC36}(s) + a_{46}\,\Delta P_{TieAC46}(s) + a_{56}\,\Delta P_{TieAC56}(s) + \Delta P_{TieFACTS612}(s)$
= [(-1) 180 + (-1) 180 + (-1) 180 + (-1) 180 + (-1) 180 + {200}]
= [(-900) + {200}] = -700 MW

$\Delta P_{TieDC6}(s) = a_{16}\,\Delta P_{TieDC1}(s) + a_{26}\,\Delta P_{TieDC2}(s) + a_{36}\,\Delta P_{TieDC3}(s) + a_{46}\,\Delta P_{TieDC4}(s) + a_{56}\,\Delta P_{TieDC5}(s) + \{\Delta P_{TieDC612}(s) = 0\}$
$= a_{16}\,\Delta P_{TieDC16}(s) + a_{26}\,\Delta P_{TieDC26}(s) + a_{36}\,\Delta P_{TieDC36}(s) + a_{46}\,\Delta P_{TieDC46}(s) + a_{56}\,\Delta P_{TieDC56}(s) + \{0\}$
= [(-1) 20 + (-1) 20 + (-1) 20 + (-1) 20 + (-1) 20 + {0}] = -100 MW
$\Delta P_{Tie6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s)$ = [(-900) + {200} + (-100)] = -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:
$\Delta P_{TieAC12}(s) = a_{612}\,\Delta P_{TieFACTS612}(s) + a_{712}\,\Delta P_{TieAC712}(s) + a_{812}\,\Delta P_{TieAC812}(s) + a_{912}\,\Delta P_{TieAC912}(s) + a_{1012}\,\Delta P_{TieAC1012}(s) + a_{1112}\,\Delta P_{TieAC1112}(s)$
= [{(-1) 200} + (-1) 180 + (-1) 180 + (-1) 180 + (-1) 180 + (-1) 180]
= [{-200} + (-900)] = -1100 MW

$\Delta P_{TieDC12}(s) = a_{612}\,\{\Delta P_{TieDC612}(s) = 0\} + a_{712}\,\Delta P_{TieDC712}(s) + a_{812}\,\Delta P_{TieDC812}(s) + a_{912}\,\Delta P_{TieDC912}(s) + a_{1012}\,\Delta P_{TieDC1012}(s) + a_{1112}\,\Delta P_{TieDC1112}(s)$
= [{0} + (-1) 20 + (-1) 20 + (-1) 20 + (-1) 20 + (-1) 20]
= -100 MW

$\Delta P_{Tie12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s)$ = [{-200} + (-900) + (-100)] = -1200 MW

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

MATLAB SIMULINK MODEL OF 12-AREA TWO INTERCONNECTED THERMAL POWER GRID WITH CASE-1 AND CASE-2.

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

The simulink model of 12-area two interconnected thermal power grid with case-1 as shown in Figure 3.

The Simulink model of 12-Area two interconnected thermal power grid with Case-2 as shown in Figure 4.

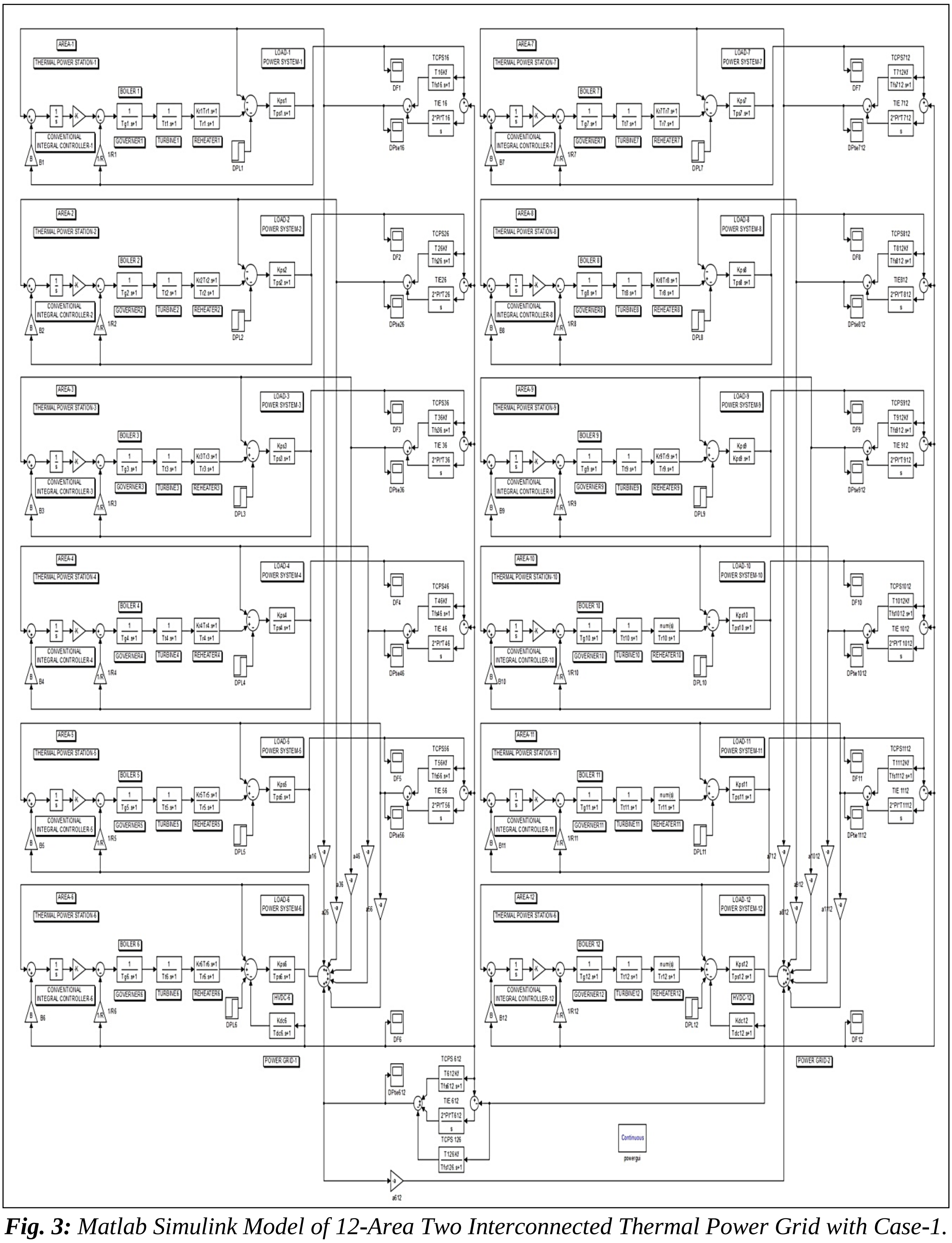

Fig. 3: *Matlab Simulink Model of 12-Area Two Interconnected Thermal Power Grid with Case-1.*

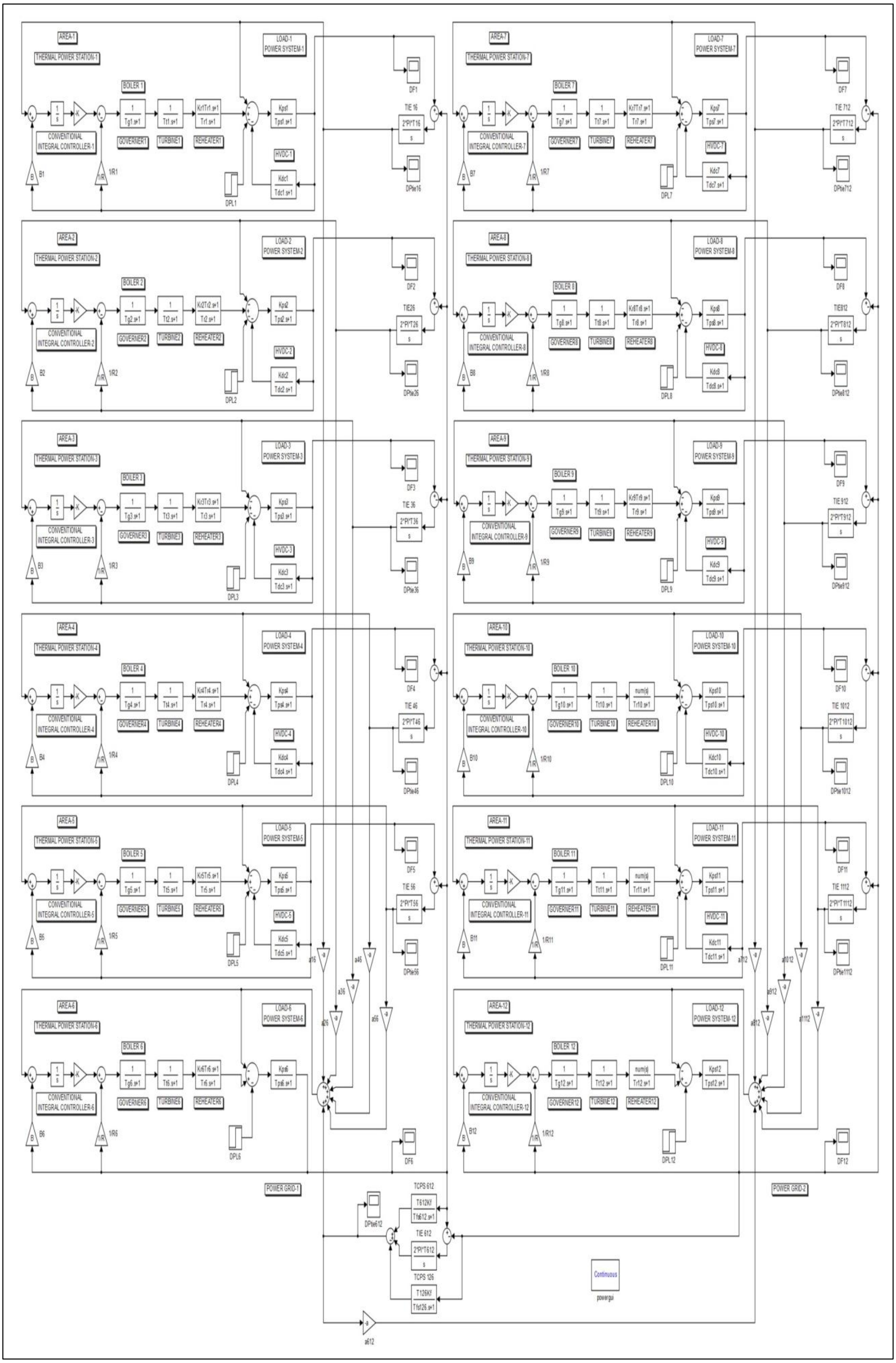

Fig. 4: *MATLAB Simulink Model of 12-Area Two Interconnected Thermal Power Grid with Case-2.*

MATLAB SIMULATION OUTPUT OF 12-AREA TWO INTERCONNECTED THERMAL POWER GRID WITH CASE-1 AND CASE-2

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

MATLAB simulation output of 12-Area two interconnected thermal power grid with Case-1 as shown in Figures 5–8.

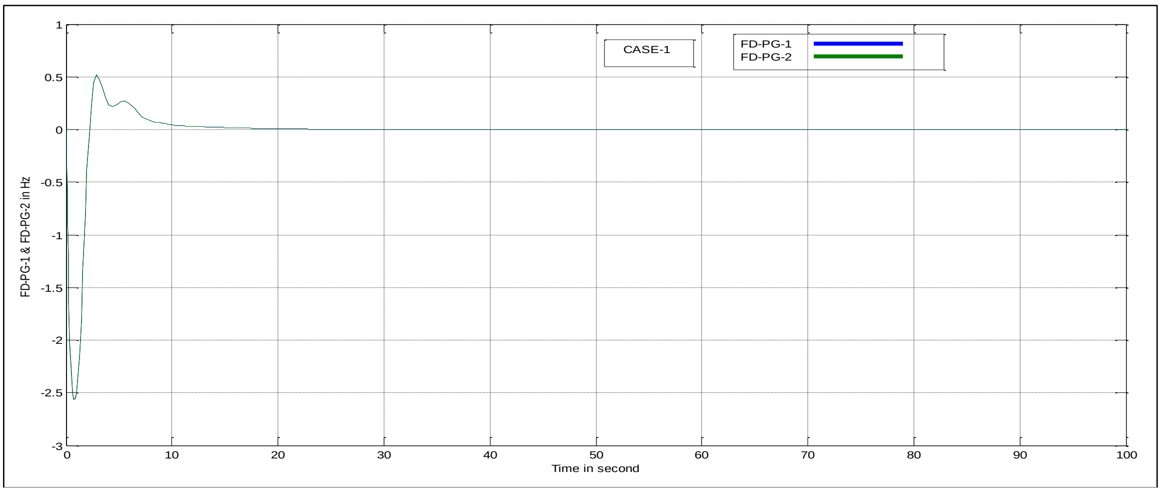

Fig. 5: *Waveform of FD-PG-1 and FD-PG-2 with Case-1.*

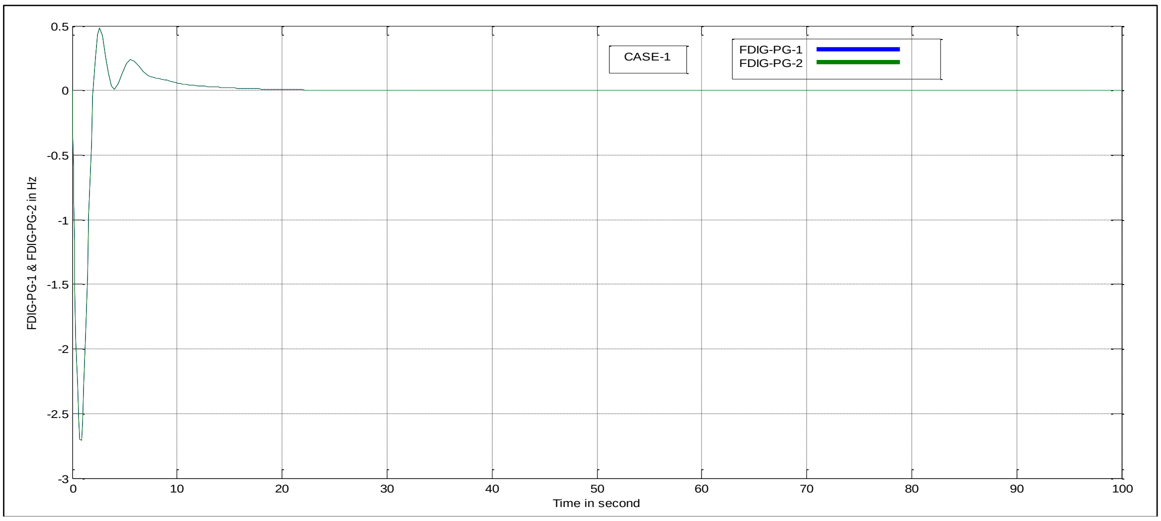

Fig. 6: *Waveform of FDIG-PG-1 and FDIG-PG-2 with Case-1.*

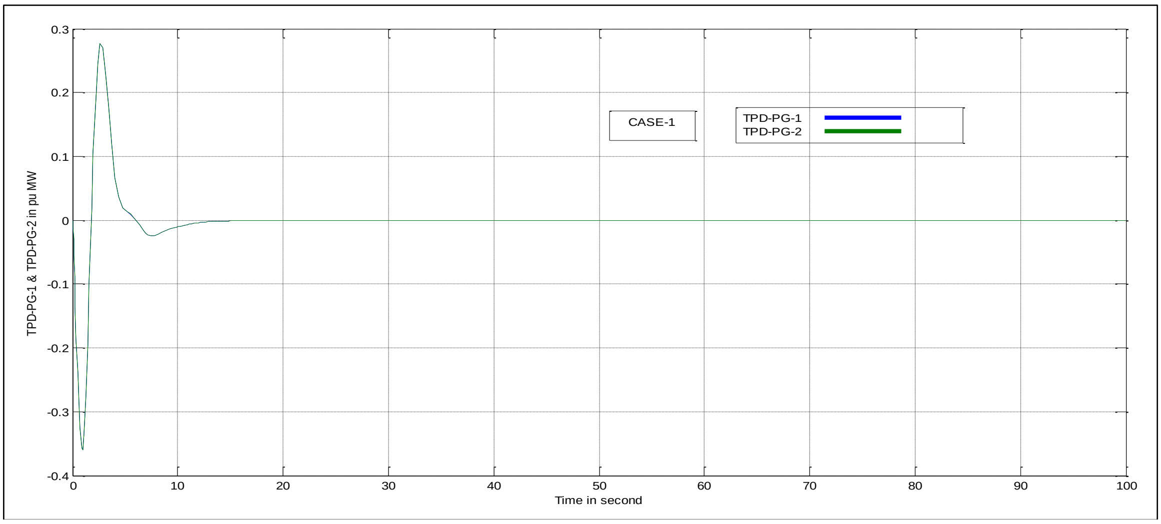

Fig. 7: *Waveform of TPD-PG-1 and TPD-PG-2 with Case-1.*

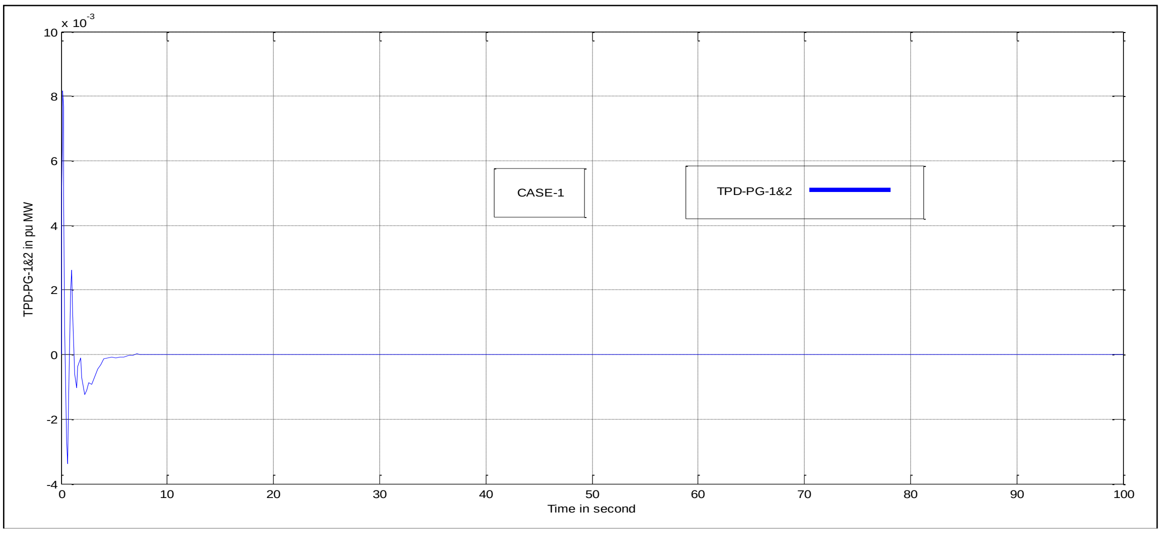

Fig. 8: *Waveform of TPD-PG-1 and 2 with Case-1.*

MATLAB simulation output of 12-Area two interconnected thermal power grid with Case-2 as shown in Figures 9–12.

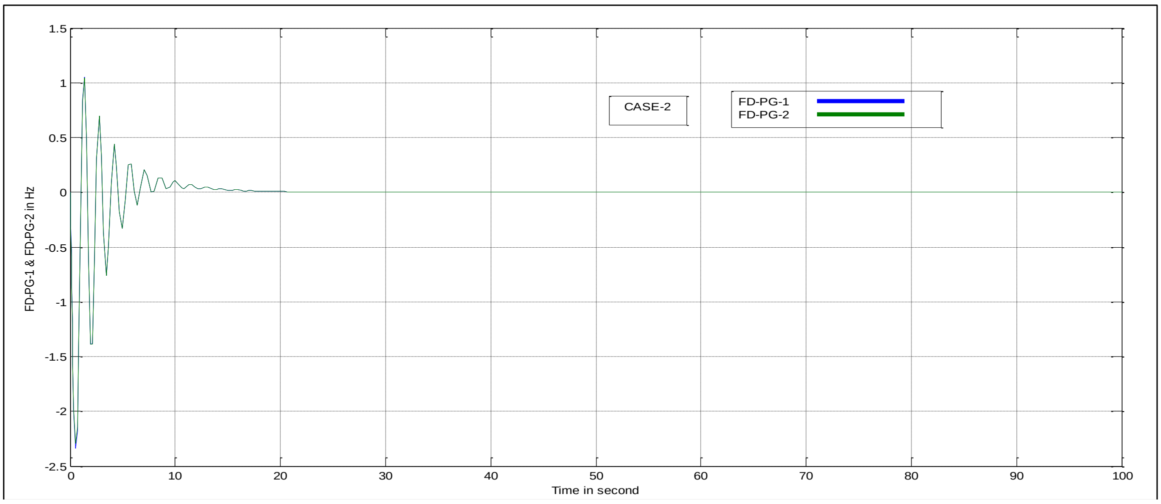

Fig. 9: *Waveform of FD-PG-1 Aand FD-PG-2 Case-2.*

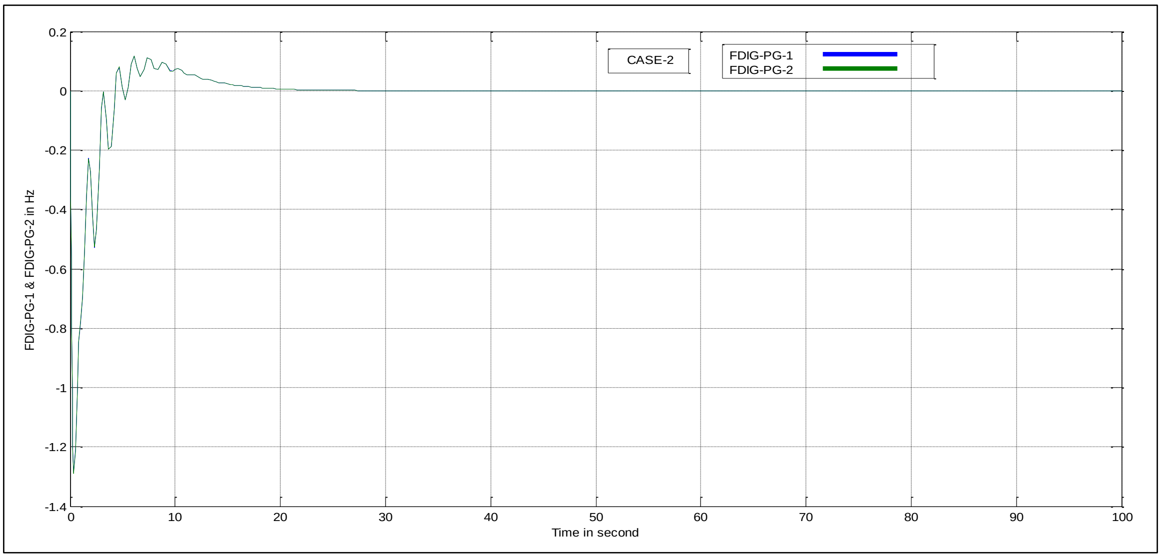

Fig. 10: *Waveform of FDIG-PG-1and FDIG-PG-2 with Case-2.*

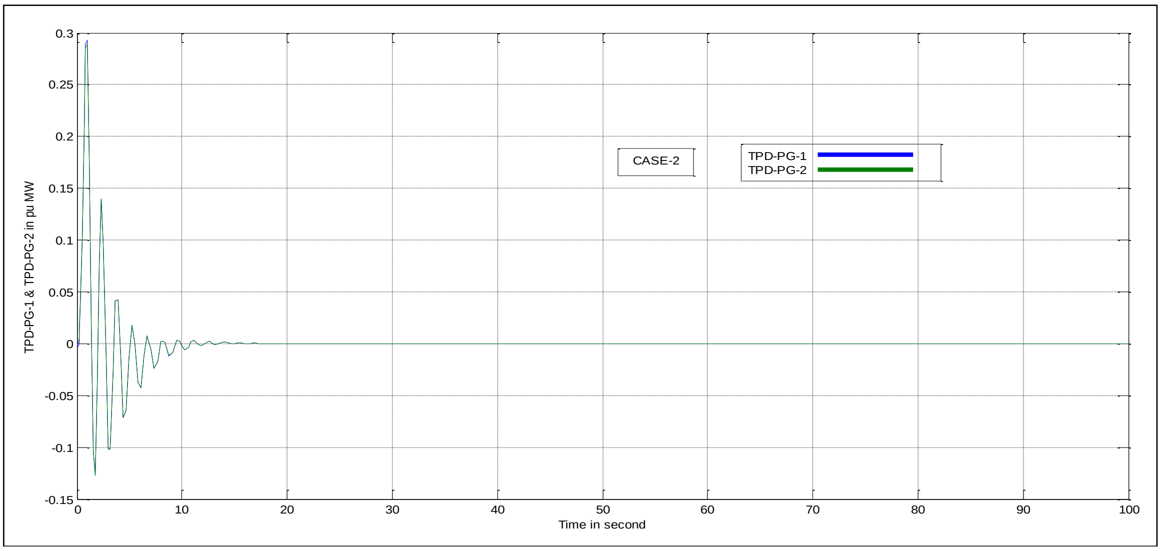

Fig. 11: *Waveform of TPD-PG-1, TPD-PG-2 with Case-2.*

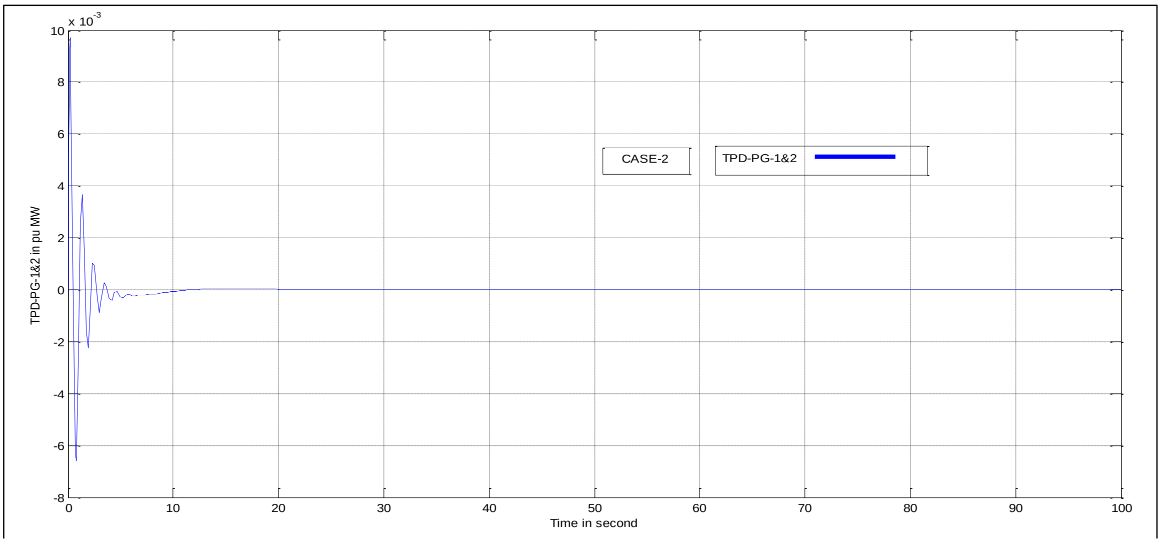

Fig. 12: *Waveform of TPD-PG-1 and 2 with Case-2.*

MATLAB SIMULATION RESULT OF 12-AREA TWO INTERCONNECTED THERMAL POWER GRID WITH CASE-1 AND CASE-2.

The simulation is done in MATLAB Software-Math Works, Volume Version 8.1.0.604 (R2013a).After load changed in power grid-1 (area-6)(ΔP_{L6} = 0.01pu), power grid-1and power grid-2 is synchronized at 22.72 sec in case-1 and power grid-1 and power grid-2 is synchronized at 20.38 sec. Settling time of frequency and tie-line power deviation of 12-area two interconnected thermal power grid with case-1 and case-2 are presents in Table 1.

Table 1: *Settling Time of Frequency and Tie-Line Power Deviation of 12-Area Two Interconnected Thermal Power Grid with Case-1 and Case-2 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 Case-1 (in sec)	Settling time with Case-2 (in sec)
FD-PG-1	22.72 sec	20.38 sec
FD-PG-2	22.72 sec	20.38 sec
FDIG-PG-1	21.91 sec	27.09 sec
FDIG-PG-2	21.91 sec	27.09 sec
TPD-PG-1	14.75 sec	16.97 sec
TPD-PG-2	14.75 sec	16.97 sec
TPD-PG-1 and 2	7.447 sec	20.00 sec

CONCLUSION

Power system dynamics performance of Case-2 is better as compare to the Case-1 in synchronization of 12-area two interconnected thermal power grid after ΔP_{L6} = 0.01pu load changed in power grid-1 (area-6).

(1) Quality of power system dynamics performance of Case-2 is better as compare to the Case-1 because in Case-2 first power grid-1 and power grid-2 is settled in 20.38 sec then its interconnected individual areas are settled in 27.09 sec.
(2) Quality of power system dynamics performance of Case-1 is closer to the Case-2 because presence of HVDC LINK in parallel with FACTS tie-line. In Case-1 first individual interconnected areas are settled in 21.91 sec then power grid-1 and power grid-2 is settled in 22.72 sec.

Finally says the order for power system dynamics performance improvement byusing Case-1 and Case-2 for synchronization of 12-area two interconnected thermal power grid in case of load change is:

Case-1 < Case-2.

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