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Synchronization of Power Grid by HVDC Technology

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Abstract - **This research work expose the advantages of HVDC technology for synchronization of two interconnected thermal power grid of 12 areas when load disturbance occur in power grid-1. Three types of tie-lines HVAC–1HVDC parallel tie-line, HVAC– 2HVDC parallel tie-line and HVAC–3HVDC parallel tie-line are applied for synchronization of 12 area two interconnected thermal power grid. For synchronization purpose of power grid this research work shows the HVAC–3HVDC parallel tie-line is better as compare to the HVAC–2HVDC parallel tie-line and HVAC–1HVDC parallel tie-lie. This research work also shows the HVAC–2HVDC parallel tie-line is better as compare to the HVAC–1HVDC parallel tie-line. Quality of all three types of tie-line is judged by the frequency deviation of two interconnected power grid of 12 areas when load disturbance occur in power grid-1. The biggest advantage of this research work is that the two interconnected thermal power grid of 12 areas is Synchronize by HVDC technology with traditional integral controller.**
Keywords: **Synchronization, HVAC–3HVDC parallel tie-line, HVAC–2HVDC parallel tie-line, HVAC–1HVDC parallel tie-line, HVAC–High Voltage Alternating Current, HVDC–High Voltage Direct Current, Traditional integral controller**

I. INTRODUCTION

For synchronization of two interconnected power grid of 12 areas three types of tie-line are applied.

1. HVAC–1HVDC parallel tie-line.
2. HVAC–2HVDC parallel tie-line.
3. HVAC–3HVDC parallel tie-line.

Load disturbance in power grid-1 is $\Delta P_{L6} = 0.01$p.u.
For synchronization of two interconnected power grid of 12 areas, frequency correction is done by tradition integral controller with three different types of tie-line above shows and any non-linear power system elements are not considered. That is the major advantage of this research work.

A. Details of Two Interconnected Thermal Power Grid

Power Grid-1 (Control Area-6): Power grid-1 is receiving power from its individual interconnected areas (control area-5, control area-4, control area-3, control area-2, control area-1) & sending power to power grid-2.

Power Grid-2 (Control Area-12): Power grid-2 is receiving power from its individual interconnected areas (control area-11, Control area-10, control area-9, control area-8, control area-7) and power grid-1.

Sahu Pankaj Kumar [18], this research work shows the advantage of HVAC-HVDC parallel tie-line over FACTS tie-line & normal HVAC tie-line. In this research work performance analysis of all three types of tie-line is done in terms of settling time of frequency and tie-line power deviation of two interconnected thermal power grid of 12 areas in case of load change in power grid-1.

Sahu Pankaj Kumar [19], this research work shows the advantage of combined application of FACTS and HVDC parallel tie-line for interconnection & synchronization of large thermal power grid. In this research work two combined cases of FACTS-HVDC parallel tie-line is applied for interconnection & synchronization of large power grid. Case-2 is better as compare to the Case-1.

Majority of research work is done only with HVAC tie-line with two area or multi area power system by power system researcher regarding the Automatic Generation Control (AGC) or Load Frequency Control (LFC) or Synchronization. For improvement of power system dynamic performance of the system in case of small disturbance with greater stability margins the HVDC is operating in parallel with HVAC tie-line [2, 9].

Other research work of synchronization or load frequency control with HVAC-HVDC parallel tie-line as shown in [1, 3-8, 10-16].

II. MATHEMETICAL MODEL OF TIE-LINE POWER EXCHANGE

A. HVAC–1HVDC Parallel Tie-Line Applied for Synchronization of Two Interconnected Thermal Power Grid of 12 Areas

The Two Interconnected Thermal Power Grid of 12 Areas with HVAC–1HVDC parallel tie-line as shown in figure-(1).
The HVAC-1HVDC parallel tie-line as shown in figure-(2).
The tie-line power equation of power grid-1 (control area-6) is $\Delta P_{Tie6}(s)$, then

$$\Delta P_{Tie6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s) \quad (1)$$

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

$$\Delta P_{TieAC6}(s) = a_{16}\ \Delta P_{TieAC16}(s) + a_{26}\ \Delta P_{TieAC26}(s) + a_{36}\ \Delta P_{TieAC36}(s) + a_{46}\ \Delta P_{TieAC46}(s) + a_{56}\ \Delta P_{TieAC56}(s) + \Delta P_{TieAC612}(s) \quad (2)$$

$$\Delta P_{TieDC6}(s) = a_{16}\ \Delta P_{TieDC16}(s) + a_{26}\ \Delta P_{TieDC26}(s) + a_{36}\ \Delta P_{TieDC36}(s) + a_{46}\ \Delta P_{TieDC46}(s) + a_{56}\ \Delta P_{TieDC56}(s) + \Delta P_{TieDC612}(s) \quad (3)$$

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

$$\Delta P_{Tie12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s) \quad (4)$$

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

$$\Delta P_{TieAC12}(s) = a_{612}\ \Delta P_{TieAC612}(s) + a_{712}\ \Delta P_{TieAC712}(s) + a_{812}\ \Delta P_{TieAC812}(s) + a_{912}\ \Delta P_{TieAC912}(s) + a_{1012}\ \Delta P_{TieAC1012}(s) + a_{1112}\ \Delta P_{TieAC1112}(s) \quad (5)$$

$$\Delta P_{TieDC12}(s) = a_{612}\ \Delta P_{TieDC612}(s) + a_{712}\ \Delta P_{TieDC712}(s) + a_{812}\ \Delta P_{TieDC812}(s) + a_{912}\ \Delta P_{TieDC912}(s) + a_{1012}\ \Delta P_{TieDC1012}(s) + a_{1112}\ \Delta P_{TieDC1112}(s) \quad (6)$$

B. HVAC–2HVDC Parallel Tie-Line Applied for Synchronization of Two Interconnected Thermal Power Grid of 12 Areas

The HVAC-2HVDC parallel tie-line as shown in figure-(3).

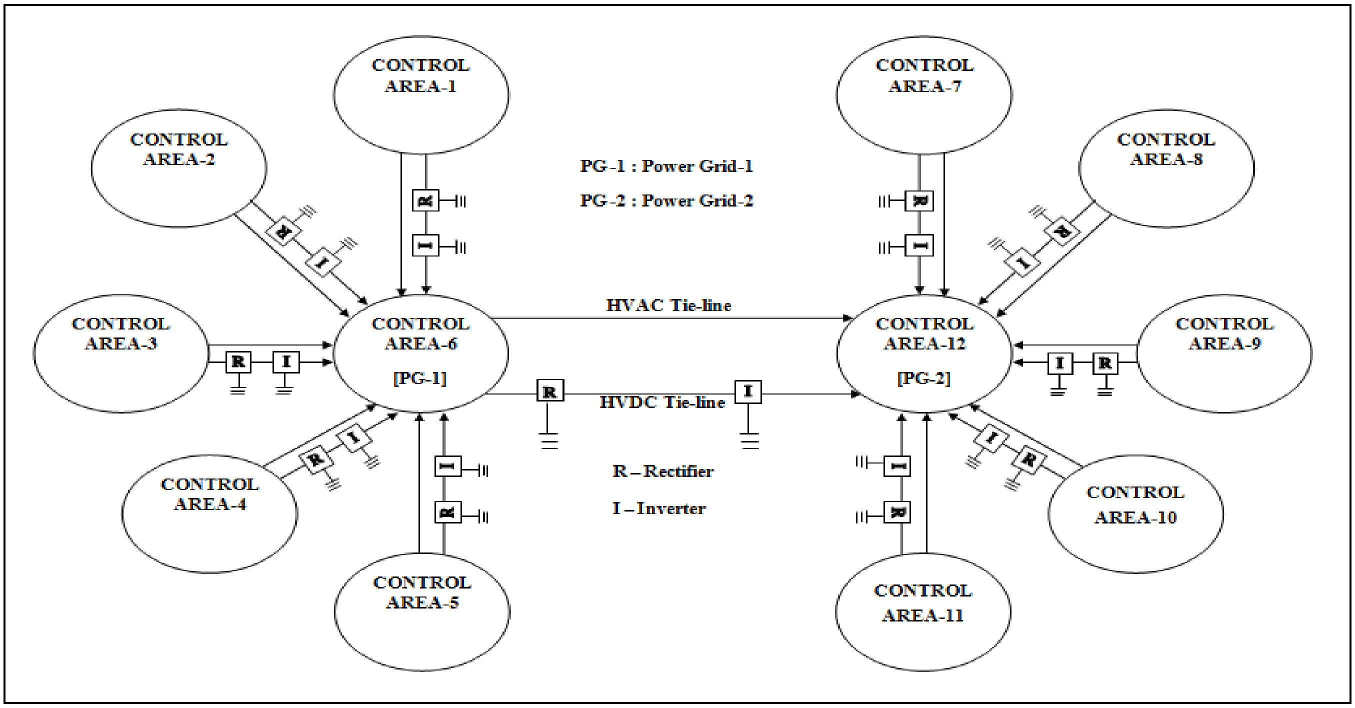

Fig. 1 The Two Interconnected Thermal Power Grid of 12 Areas with HVAC-1HVDC parallel tie-line.

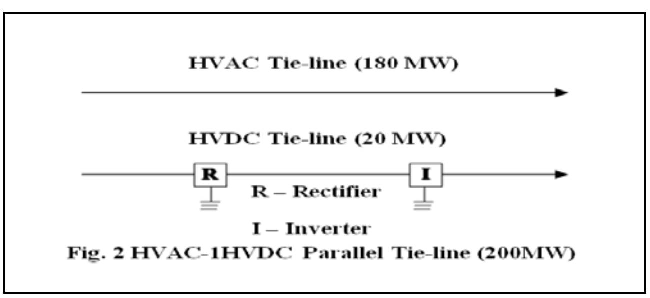

Fig. 2 HVAC–1HVDC parallel tie-line

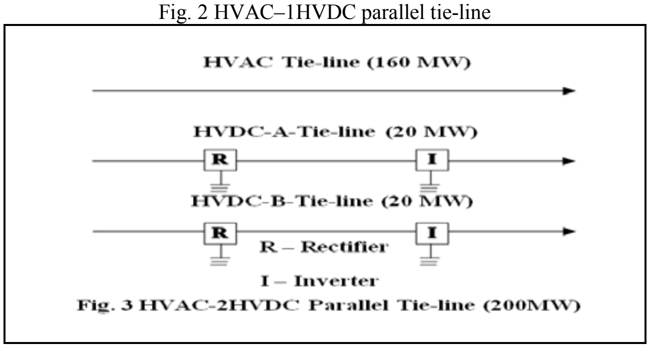

Fig. 3 HVAC–2HVDC parallel tie-line

If HVAC–2HVDC parallel tie-line is applied for synchronization of two interconnected thermal power grid of 12 areas in figure-(1), then the tie-line power equation of power grid-1 and power grid-2 are following:

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

$$\Delta P_{Tie6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6A}(s) + \Delta P_{TieDC6B}(s) \quad (7)$$

Where $\Delta P_{TieAC6}(s)$, $\Delta P_{TieDC6A}(s)$ and $\Delta P_{TieDC6B}(s)$ are,

$$\Delta P_{TieAC6}(s) = a_{16}\ \Delta P_{TieAC16}(s) + a_{26}\ \Delta P_{TieAC26}(s) + a_{36}\ \Delta P_{TieAC36}(s) + a_{46}\ \Delta P_{TieAC46}(s) + a_{56}\ \Delta P_{TieAC56}(s) + \Delta P_{TieAC612}(s) \quad (8)$$

$$\Delta P_{TieDC6A}(s) = a_{16}\ \Delta P_{TieDC16A}(s) + a_{26}\ \Delta P_{TieDC26A}(s) + a_{36}\ \Delta P_{TieDC36A}(s) + a_{46}\ \Delta P_{TieDC46A}(s) + a_{56}\ \Delta P_{TieDC56A}(s) + \Delta P_{TieDC612A}(s) \quad (9)$$

$$\Delta P_{TieDC6B}(s) = a_{16}\ \Delta P_{TieDC16B}(s) + a_{26}\ \Delta P_{TieDC26B}(s) + a_{36}\ \Delta P_{TieDC36B}(s) + a_{46}\ \Delta P_{TieDC46B}(s) + a_{56}\ \Delta P_{TieDC56B}(s) + \Delta P_{TieDC612B}(s) \quad (10)$$

$$\Delta P_{TieDC6}(s) = \Delta P_{TieDC6A}(s) + \Delta P_{TieDC6B}(s) \quad (11)$$

$$= a_{16}\ \{\Delta P_{TieDC16A}(s) + \Delta P_{TieDC16B}(s)\} + a_{26}\ \{\Delta P_{TieDC26A}(s) + \Delta P_{TieDC26B}(s)\} + a_{36}\ \{\Delta P_{TieDC36A}(s) +$$

$\Delta P_{TieDC36B}(s)\} + a_{46} \{\Delta P_{TieDC46A}(s) + \Delta P_{TieDC46B}(s)\} + a_{56} \{\Delta P_{TieDC56A}(s) + \Delta P_{TieDC56B}(s)\} + \{\Delta P_{TieDC612A}(s) + \Delta P_{TieDC612B}(s)\}$ (12)

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

$\Delta P_{Tie12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12A}(s) + \Delta P_{TieDC12B}(s)$ (13)

Where $\Delta P_{TieAC12}(s)$, $\Delta P_{TieDC12A}(s)$ and $\Delta P_{TieDC12B}(s)$ are,

$\Delta P_{TieAC12}(s) = a_{612}\ \Delta P_{TieAC612}(s) + a_{712}\ \Delta P_{TieAC712}(s) + a_{812}\ \Delta P_{TieAC812}(s) + a_{912}\ \Delta P_{TieAC912}(s) + a_{1012}\ \Delta P_{TieAC1012}(s) + a_{1112}\ \Delta P_{TieAC1112}(s)$ (14)

$\Delta P_{TieDC12A}(s) = a_{612}\ \Delta P_{TieDC612A}(s) + a_{712}\ \Delta P_{TieDC712A}(s) + a_{812}\ \Delta P_{TieDC812A}(s) + a_{912}\ \Delta P_{TieDC912A}(s) + a_{1012}\ \Delta P_{TieDC1012A}(s) + a_{1112}\ \Delta P_{TieDC1112A}(s)$ (15)

$\Delta P_{TieDC12B}(s) = a_{612}\ \Delta P_{TieDC612B}(s) + a_{712}\ \Delta P_{TieDC712B}(s) + a_{812}\ \Delta P_{TieDC812B}(s) + a_{912}\ \Delta P_{TieDC912B}(s) + a_{1012}\ \Delta P_{TieDC1012B}(s) + a_{1112}\ \Delta P_{TieDC1112B}(s)$ (16)

$\Delta P_{TieDC12}(s) = \Delta P_{TieDC12A}(s) + \Delta P_{TieDC12B}(s)$ (17)

$= a_{612} \{\Delta P_{TieDC612A}(s) + \Delta P_{TieDC612B}(s)\} + a_{712} \{\Delta P_{TieDC712A}(s) + \Delta P_{TieDC712B}(s)\} + a_{812} \{\Delta P_{TieDC812A}(s) + \Delta P_{TieDC812B}(s)\} + a_{912} \{\Delta P_{TieDC912A}(s) + \Delta P_{TieDC912B}(s)\} + a_{1012} \{\Delta P_{TieDC1012A}(s) + \Delta P_{TieDC1012B}(s)\} + a_{1112} \{\Delta P_{TieDC1112A}(s) + \Delta P_{TieDC1112B}(s)\}$ (18)

C. HVAC–3HVDC Parallel Tie-Line Applied for Synchronization of Two Interconnected Thermal Power Grid of 12 Areas

The HVAC-3HVDC parallel tie-line as shown in figure-(4).

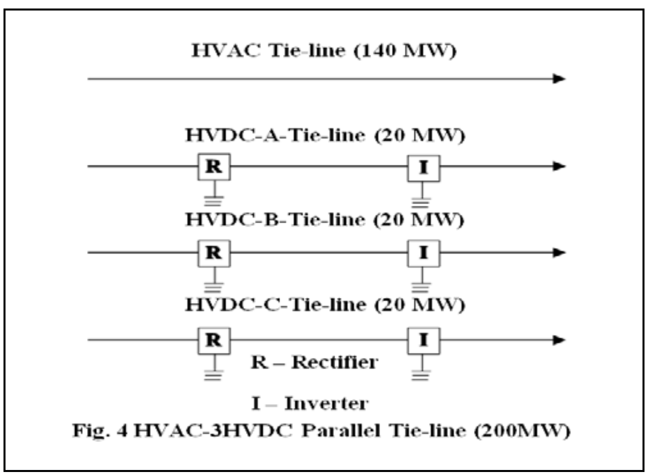

Fig. 4 HVAC–3HVDC parallel tie-line

If HVAC–3HVDC parallel tie-line is applied for synchronization of two interconnected thermal power grid of 12 areas in figure-(1), then the tie-line power equation of power grid-1 and power grid-2 are following:

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

$\Delta P_{Tie6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6A}(s) + \Delta P_{TieDC6B}(s) + \Delta P_{TieDC6C}(s)$ (19)

Where $\Delta P_{TieAC6}(s)$, $\Delta P_{TieDC6A}(s)$, $\Delta P_{TieDC6B}(s)$ and $\Delta P_{TieDC6C}(s)$ are,

$\Delta P_{TieAC6}(s) = a_{16}\ \Delta P_{TieAC16}(s) + a_{26}\ \Delta P_{TieAC26}(s) + a_{36}\ \Delta P_{TieAC36}(s) + a_{46}\ \Delta P_{TieAC46}(s) + a_{56}\ \Delta P_{TieAC56}(s) + \Delta P_{TieAC612}(s)$ (20)

$\Delta P_{TieDC6A}(s) = a_{16}\ \Delta P_{TieDC16A}(s) + a_{26}\ \Delta P_{TieDC26A}(s) + a_{36}\ \Delta P_{TieDC36A}(s) + a_{46}\ \Delta P_{TieDC46A}(s) + a_{56}\ \Delta P_{TieDC56A}(s) + \Delta P_{TieDC612A}(s)$ (21)

$\Delta P_{TieDC6B}(s) = a_{16}\ \Delta P_{TieDC16B}(s) + a_{26}\ \Delta P_{TieDC26B}(s) + a_{36}\ \Delta P_{TieDC36B}(s) + a_{46}\ \Delta P_{TieDC46B}(s) + a_{56}\ \Delta P_{TieDC56B}(s) + \Delta P_{TieDC612B}(s)$ (22)

$\Delta P_{TieDC6C}(s) = a_{16}\ \Delta P_{TieDC16C}(s) + a_{26}\ \Delta P_{TieDC26C}(s) + a_{36}\ \Delta P_{TieDC36C}(s) + a_{46}\ \Delta P_{TieDC46C}(s) + a_{56}\ \Delta P_{TieDC56C}(s) + \Delta P_{TieDC612C}(s)$ (23)

$\Delta P_{TieDC6}(s) = \Delta P_{TieDC6A}(s) + \Delta P_{TieDC6B}(s) + \Delta P_{TieDC6C}(s)$ (24)

$= a_{16} \{\Delta P_{TieDC16A}(s) + \Delta P_{TieDC16B}(s) + \Delta P_{TieDC16C}(s)\} + a_{26} \{\Delta P_{TieDC26A}(s) + \Delta P_{TieDC26B}(s) + \Delta P_{TieDC26C}(s)\} + a_{36} \{\Delta P_{TieDC36A}(s) + \Delta P_{TieDC36B}(s) + \Delta P_{TieDC36C}(s)\} + a_{46} \{\Delta P_{TieDC46A}(s) + \Delta P_{TieDC46B}(s) + \Delta P_{TieDC46C}(s)\} + a_{56} \{\Delta P_{TieDC56A}(s) + \Delta P_{TieDC56B}(s) + \Delta P_{TieDC56C}(s)\} + \{\Delta P_{TieDC612A}(s) + \Delta P_{TieDC612B}(s) + \Delta P_{TieDC612C}(s)\}$ (25)

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

$\Delta P_{Tie12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12A}(s) + \Delta P_{TieDC12B}(s) + \Delta P_{TieDC12C}(s)$ (26)

Where $\Delta P_{TieAC12}(s)$, $\Delta P_{TieDC12A}(s)$, $\Delta P_{TieDC12B}(s)$ and $\Delta P_{TieDC12C}(s)$ are,

$\Delta P_{TieAC12}(s) = a_{612}\ \Delta P_{TieAC612}(s) + a_{712}\ \Delta P_{TieAC712}(s) + a_{812}\ \Delta P_{TieAC812}(s) + a_{912}\ \Delta P_{TieAC912}(s) + a_{1012}\ \Delta P_{TieAC1012}(s) + a_{1112}\ \Delta P_{TieAC1112}(s)$ (27)

$\Delta P_{TieDC12A}(s) = a_{612}\ \Delta P_{TieDC612A}(s) + a_{712}\ \Delta P_{TieDC712A}(s) + a_{812}\ \Delta P_{TieDC812A}(s) + a_{912}\ \Delta P_{TieDC912A}(s) + a_{1012}\ \Delta P_{TieDC1012A}(s) + a_{1112}\ \Delta P_{TieDC1112A}(s)$ (28)

$\Delta P_{TieDC12B}(s) = a_{612}\ \Delta P_{TieDC612B}(s) + a_{712}\ \Delta P_{TieDC712B}(s) + a_{812}\ \Delta P_{TieDC812B}(s) + a_{912}\ \Delta P_{TieDC912B}(s) + a_{1012}\ \Delta P_{TieDC1012B}(s) + a_{1112}\ \Delta P_{TieDC1112B}(s)$ (29)

$\Delta P_{TieDC12C}(s) = a_{612}\ \Delta P_{TieDC612C}(s) + a_{712}\ \Delta P_{TieDC712C}(s) + a_{812}\ \Delta P_{TieDC812C}(s) + a_{912}\ \Delta P_{TieDC912C}(s) + a_{1012}\ \Delta P_{TieDC1012C}(s) + a_{1112}\ \Delta P_{TieDC1112C}(s)$ (30)

$\Delta P_{TieDC12}(s) = \Delta P_{TieDC12A}(s) + \Delta P_{TieDC12B}(s) + \Delta P_{TieDC12C}(s)$ (31)

$= a_{612} \{\Delta P_{TieDC612A}(s) + \Delta P_{TieDC612B}(s) + \Delta P_{TieDC612C}(s)\} + a_{712} \{\Delta P_{TieDC712A}(s) + \Delta P_{TieDC712B}(s) + \Delta P_{TieDC712C}(s)\} + a_{812} \{\Delta P_{TieDC812A}(s) + \Delta P_{TieDC812B}(s) + \Delta P_{TieDC812C}(s)\} + a_{912} \{\Delta P_{TieDC912A}(s) + \Delta P_{TieDC912B}(s) + \Delta P_{TieDC912C}(s)\} + a_{1012} \{\Delta P_{TieDC1012A}(s) + \Delta P_{TieDC1012B}(s) + \Delta P_{TieDC1012C}(s)\} + a_{1112} \{\Delta P_{TieDC1112A}(s) + \Delta P_{TieDC1112B}(s) + \Delta P_{TieDC1112C}(s)\}$ (32)

D. Parameters of Two Interconnected Thermal Power Grid of 12 Areas with HVAC–1HVDC parallel tie-line, HVAC–2HVDC parallel tie-line and HVAC–3HVDC parallel tie-line

The transfer function of various blocks of two interconnected thermal power grid of 12 areas with HVAC–1HVDC parallel tie-line, HVAC–2HVDC parallel tie-line and HVAC–3HVDC parallel tie-line:

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

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

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

$ACE_{(i)}(s) = B_{(i)}\,\Delta F_{(i)}(s) + \Delta P_{Tie(i)}(s)$

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

Rated capacity of two power grids and control areas 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

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

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

Governor (Boiler) time constants T_G = 0.08sec

Turbine time constants T_t = 0.3sec

Reheater gain constants K_R = 0.5sec,

Reheater turbine time constants: T_R = 10sec

Power system gain constants K_{PS} = 120Hz/puMW

Power system time constants T_{PS} = 20sec

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

Values of traditional integral control with HVAC–1HVDC parallel tie-line: $K_1 = K_2 = K_3 = K_4 = K_5 = 2.8$ & $K_6 = K_7 = K_8 = K_9 = K_{10} = K_{11} = K_{12} = 3.5$

Values of traditional integral control with HVAC–2HVDC parallel tie-line: $K_1 = K_2 = K_3 = K_4 = K_5 = 3.5$ & $K_6 = K_7 = K_8 = K_9 = K_{10} = K_{11} = K_{12} = 4.35$

Values of traditional integral control with HVAC–3HVDC parallel tie-line: $K_1 = K_2 = K_3 = K_4 = K_5 = 4.55$ & $K_6 = K_7 = K_8 = K_9 = K_{10} = K_{11} = K_{12} = 5.35$

(1) Tie-Line Power Calculation with HVAC–1HVDC Parallel Tie-Line: The tie-line power calculation with HVAC–1HVDC parallel tie-line is following:

Power Grid-1 (Control Area-6): Power grid-1 is receiving 1000 MW power from its individual interconnected areas (control area-5, control area-4, control area-3, control area-2, control area-1) & sending 200 MW power to power grid-2.

We know that $\Delta P_{Tie6}(s)$ 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 individual interconnected areas.

Power Grid-2 (Control Area-12): Power grid-2 is receiving 1000 MW power from its individual interconnected areas (control area-11, Control area-10, control area-9, control area-8, control area-7) and 200 MW power from power grid-1.

We know that $\Delta P_{Tie12}(s)$ 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 its individual interconnected areas and power grid-1.

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

Power Grid-1 (Control Area-6): Power grid-1 is receiving 1000 MW power from its individual interconnected areas (control area-5, control area-4, control area-3, control area-2, control area-1) & sending 200 MW power to power grid-2.

We know that $\Delta P_{Tie6}(s)$ is

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

$= \Delta P_{TieAC6}(s) + \Delta P_{TieDC6A}(s) + \Delta P_{TieDC6B}(s)$

Where $\Delta P_{TieAC6}(s)$, $\Delta P_{TieDC6A}(s)$ and $\Delta P_{TieDC6B}(s)$ 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) 160 + (-1) 160 + (-1) 160 + (-1) 160 + (-1) 160 + {160}] = [(-800) + {160}] = -640 MW

$\Delta P_{TieDC6A}(s) = a_{16}\ \Delta P_{TieDC16A}(s) + a_{26}\ \Delta P_{TieDC26A}(s) + a_{36}\ \Delta P_{TieDC36A}(s) + a_{46}\ \Delta P_{TieDC46A}(s) + a_{56}\ \Delta P_{TieDC56A}(s) + \Delta P_{TieDC612A}(s)$

= [(-1) 20 + (-1) 20 + (-1) 20 + (-1) 20 + (-1) 20 + {20}] = [(-100) + {20}] = -80 MW

$\Delta P_{TieDC6B}(s) = a_{16}\ \Delta P_{TieDC16B}(s) + a_{26}\ \Delta P_{TieDC26B}(s) + a_{36}\ \Delta P_{TieDC36B}(s) + a_{46}\ \Delta P_{TieDC46B}(s) + a_{56}\ \Delta P_{TieDC56B}(s) + \Delta P_{TieDC612B}(s)$

= [(-1) 20 + (-1) 20 + (-1) 20 + (-1) 20 + (-1) 20 + {20}] = [(-100) + {20}] = -80 MW

$\Delta P_{TieDC6}(s) = \Delta P_{TieDC6A}(s) + \Delta P_{TieDC6B}(s)$

= (-80) + (-80) = -160 MW

$\Delta P_{Tie6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6A}(s) + \Delta P_{TieDC6B}(s)$

= (-640) + (-80) + (-80) = -800 MW

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

Power Grid-2 (Control Area-12): Power grid-2 is receiving 1000 MW power from its individual interconnected areas (control area-11, Control area-10, control area-9, control area-8, control area-7) and 200 MW power from power grid-1.

We know that $\Delta P_{Tie12}(s)$ is

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

$= \Delta P_{TieAC12}(s) + \Delta P_{TieDC12A}(s) + \Delta P_{TieDC12B}(s)$

Where $\Delta P_{TieAC12}(s)$, $\Delta P_{TieDC12A}(s)$ and $\Delta P_{TieDC12B}(s)$ are,

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

$= [\ (-1)\ 160 + (-1)\ 160 + (-1)\ 160 + (-1)\ 160 + (-1)\ 160 + (-1)\ 160\ ] = [\ \{-160\} + (-800)\ ] = -960$ MW

$\Delta P_{TieDC12A}(s) = a_{612}\ \Delta P_{TieDC612A}(s) + a_{712}\ \Delta P_{TieDC712A}(s) + a_{812}\ \Delta P_{TieDC812A}(s) + a_{912}\ \Delta P_{TieDC912A}(s) + a_{1012}\ \Delta P_{TieDC1012A}(s) + a_{1112}\ \Delta P_{TieDC1112A}(s)$

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

$\Delta P_{TieDC12B}(s) = a_{612}\ \Delta P_{TieDC612B}(s) + a_{712}\ \Delta P_{TieDC712B}(s) + a_{812}\ \Delta P_{TieDC812B}(s) + a_{912}\ \Delta P_{TieDC912B}(s) + a_{1012}\ \Delta P_{TieDC1012B}(s) + a_{1112}\ \Delta P_{TieDC1112B}(s)$

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

$\Delta P_{TieDC12}(s) = \Delta P_{TieDC12A}(s) + \Delta P_{TieDC12B}(s)$

$= (-120) + (-120) = -240$ MW

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

$= \Delta P_{TieAC12}(s) + \Delta P_{TieDC12A}(s) + \Delta P_{TieDC12B}(s)$

$= (-960) + (-120) + (-120) = -1200$ MW

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

(3) Tie-Line Power Calculation with HVAC–3HVDC Parallel Tie-Line: The tie-line power calculation with HVAC–3HVDC parallel tie-line is following:

Power Grid-1 (Control Area-6): Power grid-1 is receiving 1000 MW power from its individual interconnected areas (control area-5, control area-4, control area-3, control area-2, control area-1) & sending 200 MW power to power grid-2.

We know that $\Delta P_{Tie6}(s)$ is

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

$= \Delta P_{TieAC6}(s) + \Delta P_{TieDC6A}(s) + \Delta P_{TieDC6B}(s) + \Delta P_{TieDC6C}(s)$

Where $\Delta P_{TieAC6}(s)$, $\Delta P_{TieDC6A}(s)$, $\Delta P_{TieDC6B}(s)$ and $\Delta P_{TieDC6C}(s)$ are,

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

$= [\ (-1)\ 140 + (-1)\ 140 + (-1)\ 140 + (-1)\ 140 + (-1)\ 140 + \{140\}\ ] = [\ (-700) + \{140\}\ ] = -560$ MW

$\Delta P_{TieDC6A}(s) = a_{16}\ \Delta P_{TieDC16A}(s) + a_{26}\ \Delta P_{TieDC26A}(s) + a_{36}\ \Delta P_{TieDC36A}(s) + a_{46}\ \Delta P_{TieDC46A}(s) + a_{56}\ \Delta P_{TieDC56A}(s) + \Delta P_{TieDC612A}(s)$

$= [\ (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + \{20\}\ ] = [\ (-100) + \{20\}] = -80$ MW

$\Delta P_{TieDC6B}(s) = a_{16}\ \Delta P_{TieDC16B}(s) + a_{26}\ \Delta P_{TieDC26B}(s) + a_{36}\ \Delta P_{TieDC36B}(s) + a_{46}\ \Delta P_{TieDC46B}(s) + a_{56}\ \Delta P_{TieDC56B}(s) + \Delta P_{TieDC612B}(s)$

$= [\ (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + \{20\}\ ] = [\ (-100) + \{20\}] = -80$ MW

$\Delta P_{TieDC6C}(s) = a_{16}\ \Delta P_{TieDC16C}(s) + a_{26}\ \Delta P_{TieDC26C}(s) + a_{36}\ \Delta P_{TieDC36C}(s) + a_{46}\ \Delta P_{TieDC46C}(s) + a_{56}\ \Delta P_{TieDC56C}(s) + \Delta P_{TieDC612C}(s)$

$= [\ (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + (-1)\ 20 + \{20\}\ ] = [\ (-100) + \{20\}] = -80$ MW

$\Delta P_{TieDC6}(s) = \Delta P_{TieDC6A}(s) + \Delta P_{TieDC6B}(s) + \Delta P_{TieDC6C}(s)$

$= (-80) + (-80) + (-80) = -240$ MW

$\Delta P_{Tie6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6}(s) = \Delta P_{TieAC6}(s) + \Delta P_{TieDC6A}(s) + \Delta P_{TieDC6B}(s) + \Delta P_{TieDC6C}(s)$

$= (-560) + (-80) + (-80) + (-80) = -800$ MW

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

Power Grid-2 (Control Area-12): Power grid-2 is receiving 1000 MW power from its individual interconnected areas (control area-11, Control area-10, control area-9, control area-8, control area-7) and 200 MW power from power grid-1.

We know that $\Delta P_{Tie12}(s)$ is

$\Delta P_{Tie12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12A}(s) + \Delta P_{TieDC12B}(s) + \Delta P_{TieDC12C}(s)$

Where $\Delta P_{TieAC12}(s)$, $\Delta P_{TieDC12A}(s)$, $\Delta P_{TieDC12B}(s)$ and $\Delta P_{TieDC12C}(s)$ are,

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

$= [\ (-1)\ 140 + (-1)\ 140 + (-1)\ 140 + (-1)\ 140 + (-1)\ 140 + (-1)\ 140\ ] = [\ \{-140\} + (-700)\ ] = -840$ MW

$\Delta P_{TieDC12A}(s) = a_{612}\ \Delta P_{TieDC612A}(s) + a_{712}\ \Delta P_{TieDC712A}(s) + a_{812}\ \Delta P_{TieDC812A}(s) + a_{912}\ \Delta P_{TieDC912A}(s) + a_{1012}\ \Delta P_{TieDC1012A}(s) + a_{1112}\ \Delta P_{TieDC1112A}(s)$

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

$\Delta P_{TieDC12B}(s) = a_{612}\ \Delta P_{TieDC612B}(s) + a_{712}\ \Delta P_{TieDC712B}(s) + a_{812}\ \Delta P_{TieDC812B}(s) + a_{912}\ \Delta P_{TieDC912B}(s) + a_{1012}\ \Delta P_{TieDC1012B}(s) + a_{1112}\ \Delta P_{TieDC1112B}(s)$

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

$\Delta P_{TieDC12C}(s) = a_{612}\ \Delta P_{TieDC612C}(s) + a_{712}\ \Delta P_{TieDC712C}(s) + a_{812}\ \Delta P_{TieDC812C}(s) + a_{912}\ \Delta P_{TieDC912C}(s) + a_{1012}\ \Delta P_{TieDC1012C}(s) + a_{1112}\ \Delta P_{TieDC1112C}(s)$

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

$\Delta P_{TieDC12}(s) = \Delta P_{TieDC12A}(s) + \Delta P_{TieDC12B}(s) + \Delta P_{TieDC12C}(s)$

$= (-120) + (-120) + (-120) = -360$ MW

$\Delta P_{Tie12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12}(s) = \Delta P_{TieAC12}(s) + \Delta P_{TieDC12A}(s) + \Delta P_{TieDC12B}(s) + \Delta P_{TieDC12C}(s)$

$= (-840) + (-120) + (-120) + (-120) = -1200$ MW

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

III. MATLAB (R2013a) SIMULATION MODEL

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

1. The MATLAB SIMULINK MODEL of Two Interconnected Thermal Power Grid of 12 AREAS with HVAC–1HVDC parallel tie-line as shown in figure-(5).
2. The MATLAB SIMULINK MODEL of Two Interconnected Thermal Power Grid of 12 AREA with HVAC–2HVDC parallel tie-line as shown in figure-(6).
3. The MATLAB SIMULINK MODEL of Two Interconnected Thermal Power Grid of 12 AREA with HVAC–3HVDC parallel tie-line as shown in figure-(7).

IV. MATLAB (R2013a) SIMULATION OUTPUT

Before representation of MATLAB (R2013a) SIMULATION OUTPUT of Two Interconnected Thermal Power Grid of 12 Areas with HVAC–1HVDC parallel tie-line, HVAC–2HVDC parallel tie-line and HVAC–3HVDC parallel tie-lie some definition are shown below regarding the output of this research work:

TPD-PG-1: Tie-line power deviation of Power-Grid-1
TPD-PG-1: [$\Delta P_{Tie56}(s)$, $\Delta P_{Tie46}(s)$, $\Delta P_{Tie36}(s)$, $\Delta P_{Tie26}(s)$, $\Delta P_{Tie16}(s)$]
TPD-PG-2: Tie-line power deviation of Power-Grid-2
TPD-PG-2: [$\Delta P_{Tie1112}(s)$, $\Delta P_{Tie1012}(s)$, $\Delta P_{Tie912}(s)$, $\Delta P_{Tie812}(s)$, $\Delta P_{Tie712}(s)$]
TPD-PG1&2: Tie-line power deviation between Power-Grid-1 to Power-Grid-2 [$\Delta P_{Tie612}(s)$]
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 individual interconnected group of Power-Grid-1
FDIG-PG-1: [($\Delta F_5(s)$, $\Delta F_4(s)$, $\Delta F_3(s)$, $\Delta F_2(s)$, $\Delta F_1(s)$]
FDIG-PG-2: Frequency deviation of individual interconnected group of Power-Grid-2
FDIG-PG-2: [($\Delta F_{11}(s)$, $\Delta F_{10}(s)$, $\Delta F_9(s)$, $\Delta F_8(s)$, $\Delta F_7(s)$]

A. The MATLAB (R2013a) SIMULATION OUTPUT of Two Interconnected Thermal Power Grid of 12 AREAS with HVAC–1HVDC parallel tie-line as shown in figure-(8) and figure-(9).

B. The MATLAB (R2013a) SIMULATION OUTPUT of Two Interconnected Thermal Power Grid of 12 A REAS with HVAC–2HVDC parallel tie-line as shown in figure-(10) and figure-(11).

C. The MATLAB (R2013a) SIMULATION OUTPUT of Two Interconnected Thermal Power Grid of 12 A REAS with HVAC–3HVDC parallel tie-line as shown in figure-(12) and figure-(13).

V. MATLAB (R2013a) SIMULATION RESULT

MATLAB (R2013a) Simulation Result of Synchronization of Two Interconnected Thermal Power Grid of 12 Areas with HVAC–1HVDC parallel tie-line, HVAC–2HVDC parallel tie-line & HVAC–3HVDC parallel tie-line: After ΔP_{L6} = 0.01p.u. load change in Power Grid-1/Control Area-6 Synchronization of Two Interconnected Thermal Power Grid of 12 A reas is done by HVAC–1HVDC parallel tie-line, HVAC–2HVDC parallel tie-line & HVAC–3HVDC parallel tie-line with traditional integral controller.

1. The simulation result of synchronization of two interconnected thermal power grid of 12 areas with HVAC–1HVDC parallel tie-line {from figure-(8)} as shown in Table-I.
2. The simulation result of synchronization of two interconnected thermal power grid of 12 areas with HVAC–2HVDC parallel tie-line {from figure-(10)} as shown in Table-II.
3. The simulation result of synchronization of two interconnected thermal power grid of 12 areas with HVAC–3HVDC parallel tie-line {from figure-(12)} as shown in Table-III.

It's clear from the simulation results under synchronization process frequency deviation with HVAC–3HVDC parallel tie-line is smaller as compare to the HVAC–2HVDC parallel tie-line & HVAC–1HVDC parallel tie-line. Also the frequency deviation with HVAC–2HVDC parallel tie-line is smaller as compare to the HVAC–1HVDC parallel tie-line.
Quality of HVAC–3HVDC parallel tie-line is high as compare to the HVAC–2HVDC parallel tie-line & HVAC–1HVDC parallel tie-line. Quality of HVAC–2HVDC parallel tie-line is high as compare to the HVAC–1HVDC parallel tie-line.

The SIMULATION is done with MATLAB SOFTWARE-MATH WORKS, volume version 8.1.0.604 (R2013a).

VI. CONCLUSION

Synchronizing Quality of HVAC–3HVDC parallel tie-line is best for Power Grid.

1. HVAC–3HVDC parallel tie-line shows better power system dynamic performance as compare to the HVAC–2HVDC parallel tie-line & HVAC–1HVDC parallel tie-line.
2. HVAC–2HVDC parallel tie-line shows better power system dynamic performance as compare to the HVAC–1HVDC parallel tie-line.

Finally says the order of HVAC–HVDC parallel tie-line for power system dynamics performance improvement of Two Interconnected Thermal Power Grid of 12 Areas in case of load disturbance in Power Grid-1:

HVAC–1HVDC parallel tie-line < HVAC–2HVDC parallel tie-line < HVAC–3HVDC parallel tie-line.

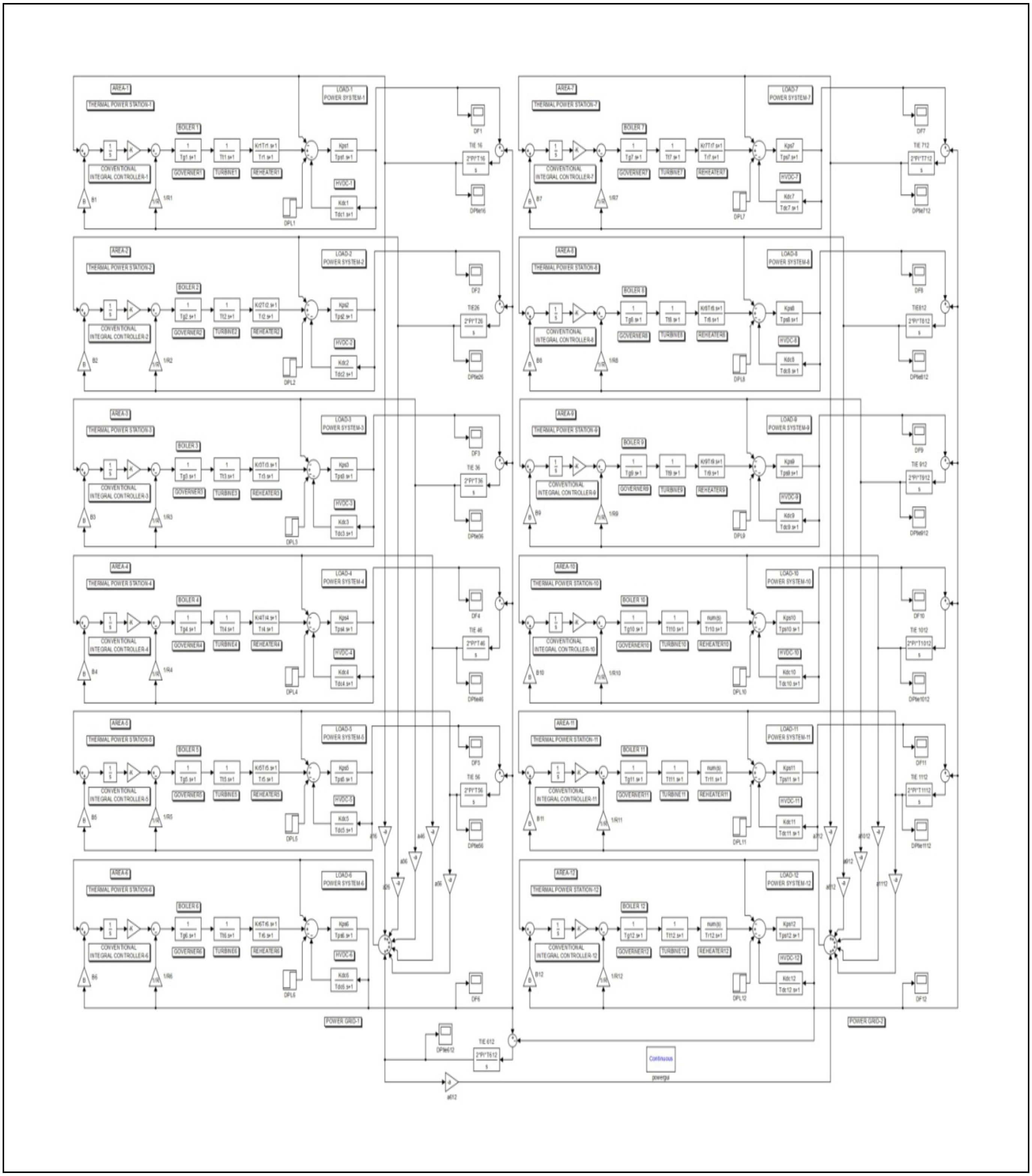

Fig. 5 MATLAB (R2013a) SIMULINK MODEL of Two Interconnected Thermal Power Grid of 12 AREAS with HVAC–1HVDC parallel tie-line

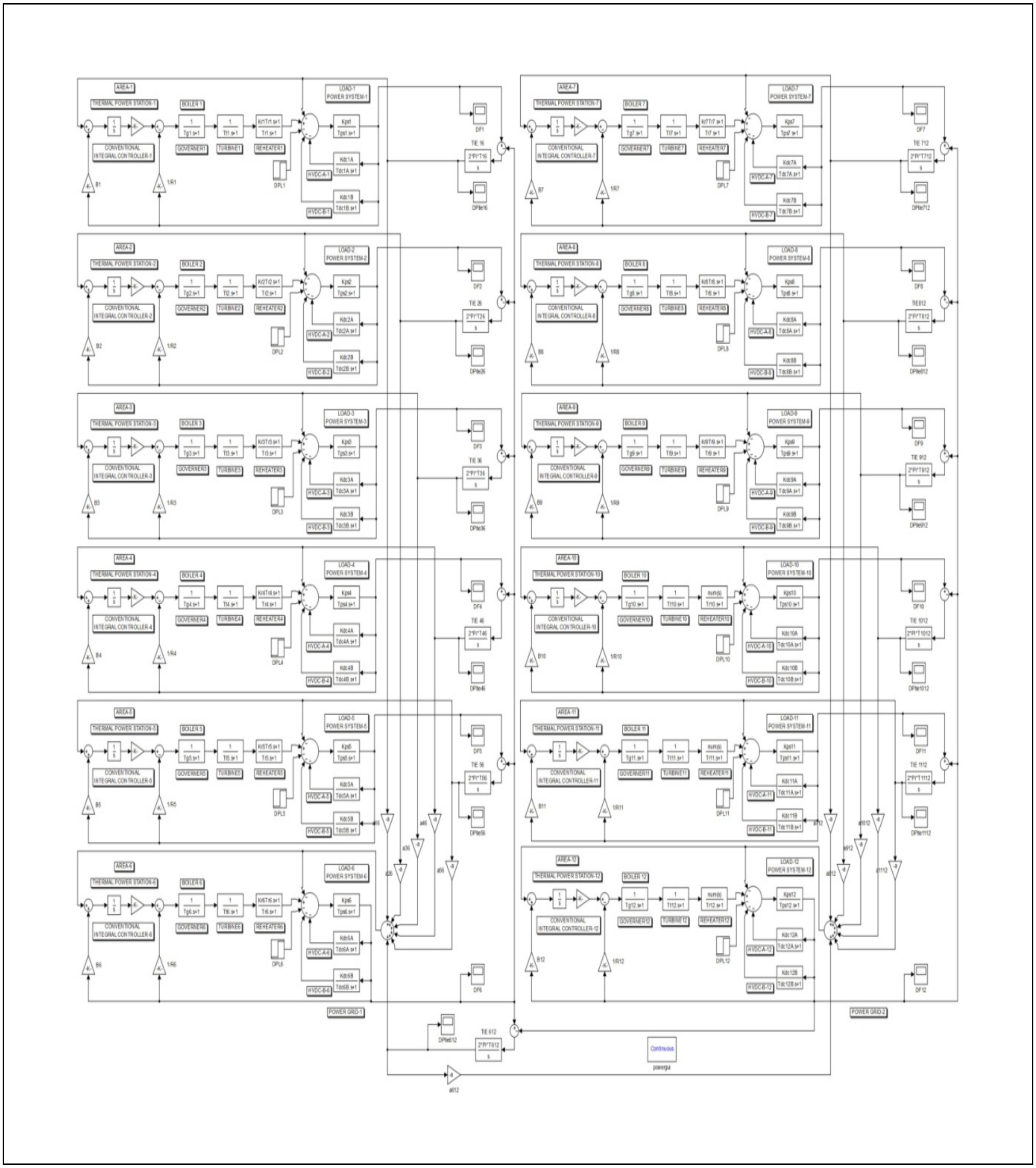

Fig. 6 MATLAB (R2013a) SIMULINK MODEL of Two Interconnected Thermal Power Grid of 12 AREAS with HVAC–2HVDC parallel tie-line

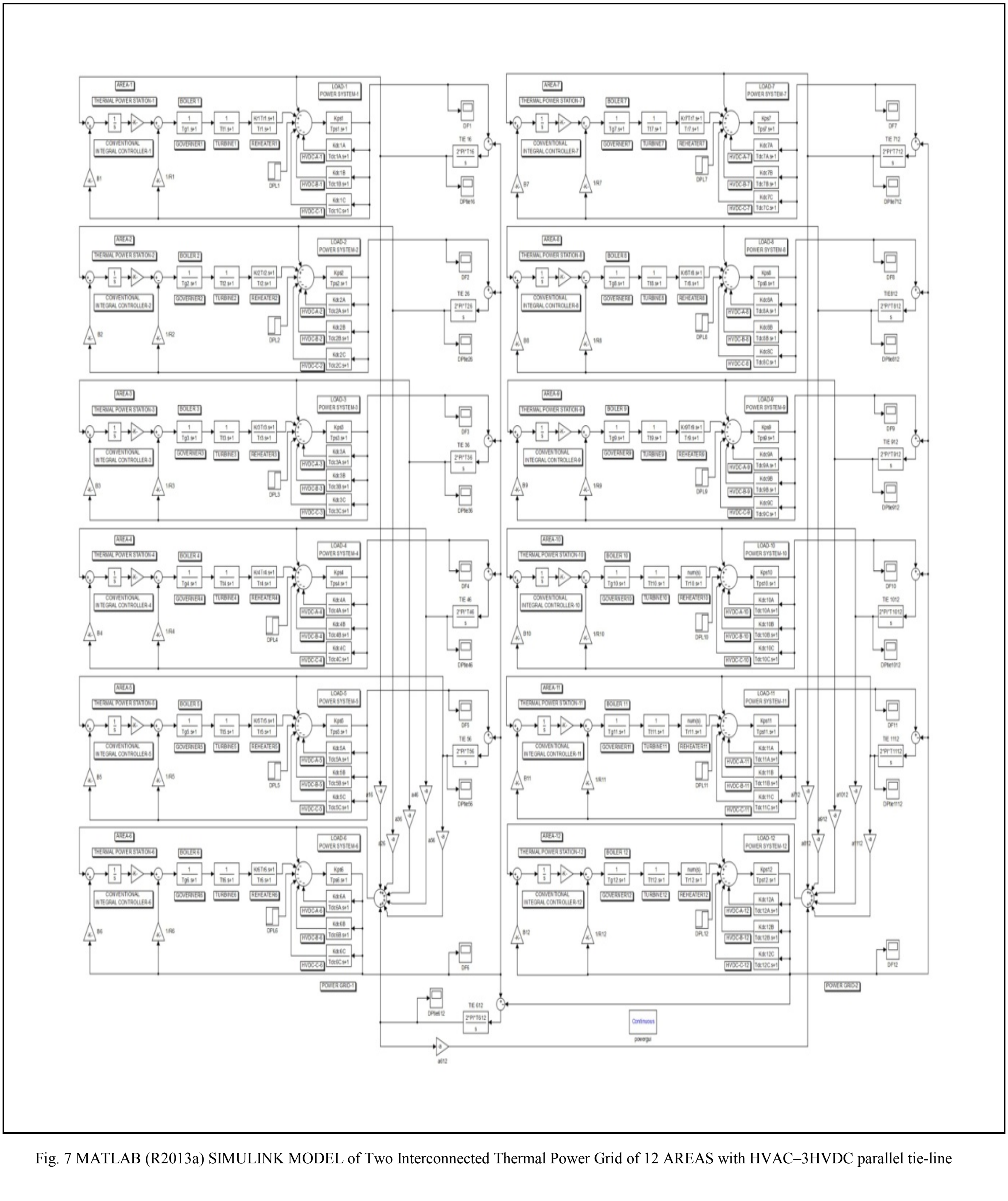

Fig. 7 MATLAB (R2013a) SIMULINK MODEL of Two Interconnected Thermal Power Grid of 12 AREAS with HVAC–3HVDC parallel tie-line

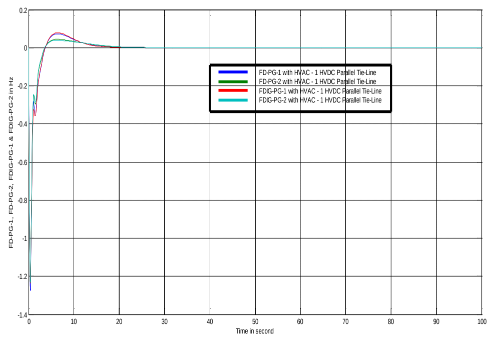

Fig. 8 Waveform of FD-PG-1, FD-PG-2, FDIG-PG-1 & FDIG-PG-2 with HVAC–1HVDC parallel tie-line

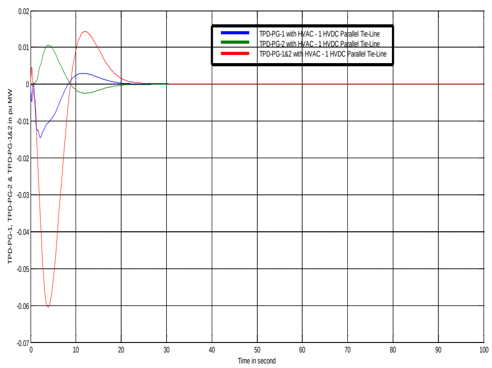

Fig. 9 Waveform of TPD-PG-1, TPD-PG-2, TPD-PG-1&2 with HVAC–1HVDC parallel tie-line

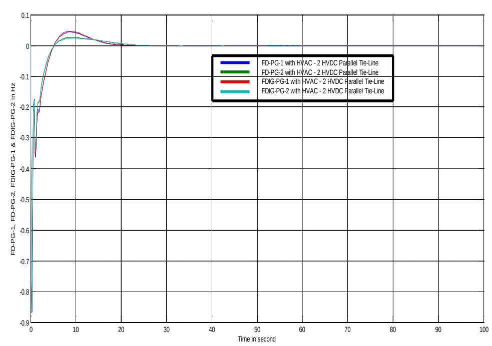

Fig. 10 Waveform of FD-PG-1, FD-PG-2, FDIG-PG-1 & FDIG-PG-2 with HVAC–2HVDC parallel tie-line

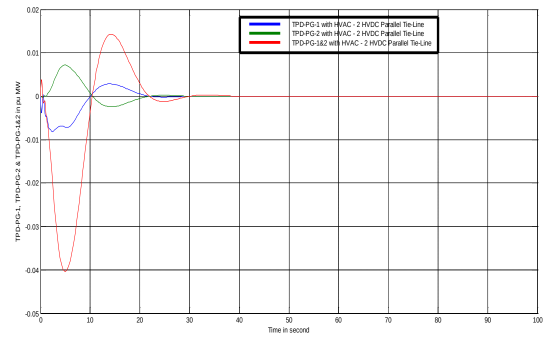

Fig. 11 Waveform of TPD-PG-1, TPD-PG-2, TPD-PG-1&2 with HVAC–2HVDC parallel tie-line

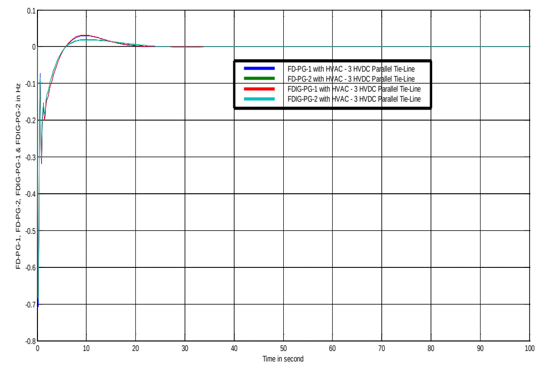

Fig. 12 Waveform of FD-PG-1, FD-PG-2, FDIG-PG-1 & FDIG-PG-2 with HVAC–3HVDC parallel tie-line

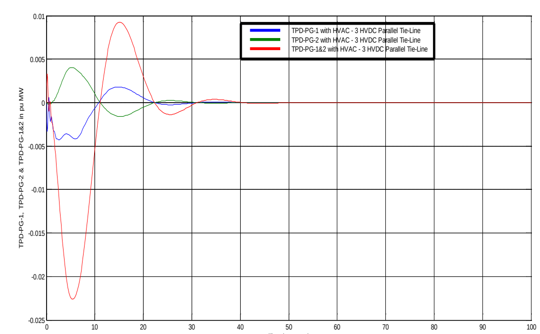

Fig. 13 Waveform of TPD-PG-1, TPD-PG-2, TPD-PG-1&2 with HVAC–3HVDC parallel tie-line

TABLE I FREQUENCY DEVIATION OF TWO INTERCONNECTED THERMAL POWER GRID OF 12 AREAS WITH HVAC-1HVDC PARALLEL TIE-LINE WHEN $\Delta P_{L6} = 0.01$P.U. LOAD CHANGE IN POWER GRID-1

Frequency Deviation	FD-PG-1	FD-PG-2	FDIG-PG-1	FDIG-PG-2
+ve Hz	0.07294	0.04367	0.07843	0.03872
–ve Hz	–1.274	–1.23	–1.236	–1.233

TABLE II FREQUENCY DEVIATION OF TWO INTERCONNECTED THERMAL POWER GRID OF 12 AREAS WITH HVAC-2HVDC PARALLEL TIE-LINE WHEN $\Delta P_{L6} = 0.01$P.U. LOAD CHANGE IN POWER GRID-1

Frequency Deviation	FD-PG-1	FD-PG-2	FDIG-PG-1	FDIG-PG-2
+ve Hz	0.04409	0.02608	0.0471	0.02296
–ve Hz	–0.8691	–0.8604	–0.8607	–0.8628

TABLE III FREQUENCY DEVIATION OF TWO INTERCONNECTED THERMAL POWER GRID OF 12 AREAS WITH HVAC-3HVDC PARALLEL TIE-LINE WHEN ΔP_{L6} = 0.01P.U. LOAD CHANGE IN POWER GRID-1

Frequency Deviation	FD-PG-1	FD-PG-2	FDIG-PG-1	FDIG-PG-2
+ve Hz	0.03019	0.02028	0.0316	0.01837
–ve Hz	–0.7083	–0.6854	–0.6857	–0.6873

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