HVDC FACTS Controller for Load Frequency Control System

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***Abstract*—power system frequency deviation is always presented result to the continuous loads variation, thus leading to build the load frequency control (LFC) systems. In this paper, HVDC systems are used to suppression such this frequency oscillations which occur result to load variation between two-area interconnected systems. A comparative evaluation between HVDC and superconducting magnetic energy storage (SMES) are introduced in this paper to make a comparative study between different controllers to improve the dynamic performances of the power system. Two-Area Power system with AC/DC parallel tie lines is simulated and then it is subjected to different disturbances. Responses of frequencies deviation, AC tie line powers deviation and area control errors have been plotted for two areas. The system Dynamic performance using HVDC FACTS Controller is superior with fast response and less overshoot/undershoot.**

***Index Term* --loads variation, LFC, dynamic, PI, HVDC, SMES.**

I. INTRODUCTION

The load frequency control system is necessary for the operation and control of the Power system to ensure the supply of suitable and reliable power with good quality. Frequency oscillations problem due to unpredictable load changes has become increased, especially in integrated power system [1, 2]. Random load changes results in mismatch power between generation and loads consumption powers, which in turn, affects the efficiency and reliability of electric power. These mismatches must to be corrected. Power system reliability and stability mainly depends upon frequency deviation [3, 4]. This can be achieved by Automatic generation control (AGC), which is the master synthesis of generation management system.

There are two main objectives of LFC; to keep the output power and the system frequency in an interconnected power system at nominal values and to maintain the net interchange of power between control areas at predetermined values [4, 5]. This goal is achieved by using adaptive controllers to control the steam valves in thermal power system or water gates of speed governors in hydro area system in which to control the Flow rate of steam or water through the turbines. As a result of this control, the mechanical power and thus the generated electrical power is matched.

HVDC enable unsynchronized connection and power transfer between two AC distribution systems. Also it can help raise system stabilization, by forbidding cascading shortage from one part of enormous power transmission part to another [6]. Power flow direction and magnitude control through a DC transmission system is easily by controlling the firing angles at both sides of the rectifier and inverter stations.

Controlling the active power through DC link can be used to upholding the AC networks which may be connected at either end of the DC link. For these reasons, the most of power grid designers have used AC lines in parallel with HVDC lines to ensure that an improved system dynamic performance [7]. Additional controls are often required to contribution the controllability of DC link for promote the AC system dynamic performance, signals such as frequency deviation or area control errors derived from the AC systems may be used as feedback signals to this additional controllers to modulate the DC power transmitted through HVDC link so that HVDC transmission lines in parallel with HVAC lines may be used to improve transient stability as well as to damp out oscillations in power system [8, 9].

Another control strategy of LFC by injecting incremental active power which is proportional to the frequency deviation [10].This can be accomplished by using FACTS devices to make active power control such as SMES devices. IEEE defines SMES as a device can be used to control the power flow through the AC system by controlling in its electronic converters in which it can injects and/or absorbs real and/or reactive power [11].

In this paper, a proposed scheme of HVDC is modeled to show the advantage of fast HVDC power modulation to improve the AC system stability under load disturbance of two area interconnected power system. Predictive PI controllers are used in both areas to control the operation of governor and turbine units of two area power system. SMES device with an appropriate control circuit is simulated and connected at two area power system to damp out frequency oscillations.

Three different strategies of the control systems using PI, HVDC and SMES for damping oscillation caused result to the load disturbance at any of two areas are introduced in this paper to make a comparative study of these controllers based on undershoot, settling time and area control errors in order to show the appropriate controller to damp out such this oscillations in two area power system.

II. TWO AREA LFC

An expanded power system can be divided into a number of LFC areas interconnected by means of tie-lines. a two-area case connected by a single AC tie-line as shown in Fig. 1.

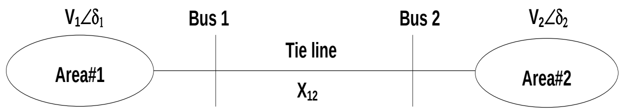

Figure 1. Two-area LFC with AC tie-line connection.

The control objective is now to adjust the frequency of each area at nominal values and to simultaneously regulate the tie-line power. Predictive PI controllers are used to reduce steady state error in tie-line power flow. Each control area can be represented by an equivalent turbine, generator and governor system.

Symbols with suffix 1 refer to area-1 and those with suffix 2 refer to area-2. In an isolated control area case, the incremental power (ΔP_G-ΔP_D) was accounted by the rate of increase of stored kinetic energy and increase in area load caused by increase in frequency. Since a tie-line transports power in or out of an area, this must be accounted as the incremental power balance equation of each area.

Power transported out of area-1 is given by:

$$\mathrm{Ptie}_{\,\mathrm{line}} = \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1 - \delta_2) \qquad (1)$$

Where:

$|V_1|, |V_2|$: The magnitude of voltages of areas 1, 2, respectively.

δ_1, δ_2: The angles of voltages of two areas1, 2, respectively.

X_{12}: The reactance value between two buses1and 2.

For incremental changes in $\delta_1$and δ_2, the incremental change in tie line power can be expressed as:

$$\Delta \mathrm{Ptie}_{\,1}(\mathrm{pu}) = T_{12}(\Delta\delta_1 - \Delta\delta_2) \qquad (2)$$

Where T_{12} is a synchronizing coefficient and it is given by:

$$T_{12} = \frac{|V_1||V_2|}{X_{12}P_{r1}} \cos(\delta_1^0 - \delta_2^0) \qquad (3)$$

Incremental changes in $\delta_1$and δ_2 can be written as function of frequency deviation of each area as follows

$$\Delta\delta_1 = 2\pi \int \Delta f_1 \, dt \;\; \& \quad \Delta\delta_2 = 2\pi \int \Delta f_2 \, dt \qquad (4)$$

$$\Delta \mathrm{Ptie}_{\,1}(\mathrm{pu}) = 2\pi T_{12} \left(\int \Delta f_1 \, dt - \int \Delta f_2 \, dt \right) \qquad (5)$$

$$\Delta \mathrm{Ptie}_{\,2}(\mathrm{pu}) = 2\pi T_{21} \left(\int \Delta f_2 \, dt - \int \Delta f_1 \, dt \right) \qquad (6)$$

Where:

$$T_{21} = \left(\frac{P_{r1}}{p_{r2}}\right) T_{12} = a_{12} T_{12} \qquad (7)$$

P_{r1}: The rated power of area-1.

Pr_2: The rated power of area-2.

a_{12}: The ratio of rated powers in two-area.

Taking Laplace transform of Equations. (5) and (6).

$$\Delta \mathrm{Ptie}_{\,1}(s) = \frac{2\pi T_{12}}{s} \left(\int \Delta F_1\,(s) - \int \Delta F_2\,(s) \right) \qquad (8)$$

$$\Delta \mathrm{Ptie}_{\,2}(s) = \frac{2\pi a_{12} T_{12}}{s} \left(\int \Delta F_1\,(s) - \int \Delta F_2\,(s) \right) \qquad (9)$$

The increment in power input to the generator-load system in each area is related to frequency change of its area as

$$\Delta F(s) = [\Delta P_G(s) - \Delta P_D(s)] * \left(\frac{K_p}{1 + T_p s} \right) \qquad (10)$$

From the above equations, it is shown that there are steady state errors of frequency deviations (ΔF_1, ΔF_2) and tie power deviation (ΔPtie) as a result of change in loads. To correct these steady-state errors, appropriate control must be given in both areas. The control signal is known as area control error (ACE). ACE for area-1 and area-2 can be given as:

$$ACE_1 = B_{f1}\Delta F_1 + \Delta P_{tie1} \qquad (11)$$

$$ACE_2 = B_{f2}\Delta F_2 + a_{12}\Delta P_{tie1} \qquad (12)$$

Where:

B_{f1}, B_{f2}: The frequency biases for area-1 and area-2, respectively.

Each power area represented by its speed governor, turbine, generator and system load transfer functions in block diagram with thermal units as shown in fig.(2).

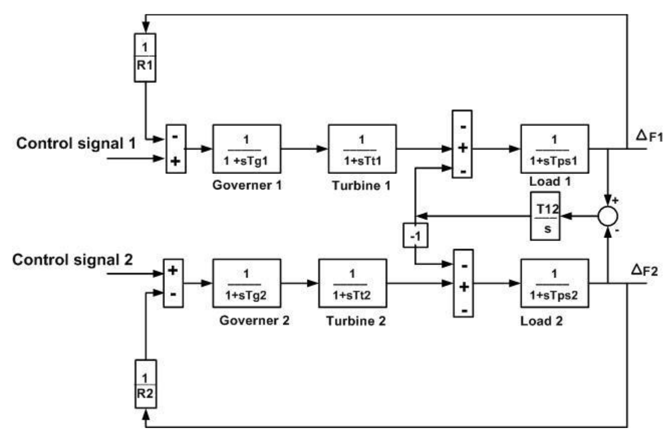

Figure 2. Block diagram of LFC of thermal two area interconnected power system.

III. HVDC Controller for Two-Area Interconnected Power System

HVDC link can be connected in parallel with an HVAC link, interconnecting control areas to get an improved AC system dynamic performance. Figure. 3 shows the single line diagram of the two areas interconnected power system with AC tie line in parallel with DC link.

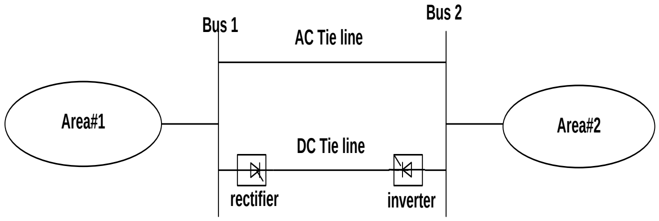

Figure 3. Two areas with AC-DC Tie-Line Connection.

Proposed HVDC scheme is considered to have special features tailored to have the specific needs of its application. The transfer function model [12] is considered for representation of a DC link. The time constant of the DC link, $T_{dc}=L_{dc}/R_{dc}$ represents the delay in establishing the DC current after a small load disturbance.

The DC link is considered to be operated in constant current control mode. The incremental power flow through DC link is modeled with incremental change in frequency at rectifier and inverter ends.

For small load perturbation at area-1, the deviation in power flow ($\Delta Ptie_{12}$) between area-1 and area-2 interconnected by AC transmission line only is $\Delta Ptie_{AC}$ given as:

$$\Delta Ptie_{AC} = \frac{T_{12}}{s}(\Delta F_1(s) - \Delta F_2(s)) \quad (13)$$

Also the DC tie-line flow, $\Delta Ptie_{DC}$ can be given as:

$$\Delta Ptie_{DC} = \frac{K_{dc}}{1 + sT_{dc}}(\Delta F_1(s) - \Delta F_2(s)) \quad (14)$$

Where $\frac{K_{dc}}{1+sT_{dc}}$ represents the transfer function of HVDC link.

The total power flow $Ptie_{12}$ can be written as:

$$Ptie_{12} = Ptie_{AC} + Ptie_{DC} \quad (15)$$

For small load perturbation:

$$\Delta Ptie_{12} = \Delta Ptie_{AC} + \Delta Ptie_{DC} \quad (16)$$

By integrating DC link in parallel with AC link, Equations. (11) And (12) of ACE of area-1 and area-2 are modified as:

$$ACE_1 = B_{f1}\Delta F_1 + (\Delta Ptie_{AC} + \Delta Ptie_{DC}) \quad (17)$$

$$ACE_2 = B_{f2}\Delta F_2 + a_{12}(\Delta Ptie_{AC} + \Delta Ptie_{DC}) \quad (18)$$

So in the proposed control scheme HVDC link works as power modulation device to supply the power to the load according to the control signal (the value of frequency deviation due to load change), This power added to the generator power to supply the load demand which reduce deviation in AC tie line power and consequently decrease ACE helping to damp oscillation in each area.

IV. SMES CONTROLLER FOR TWO-AREA INTERCONNECTED POWER SYSTEM

Figure 4 shows the equivalent circuit of SMES Unit [13].In order to study the effects of SMES units in power system, a two area systems has been considered as shown in Fig. 5, area-1 and area-2 are connected by AC tie line.

An SMES unit is connected to area-1 bus which subjected to load frequency disturbance as shown in the single line diagram of Fig. 5.

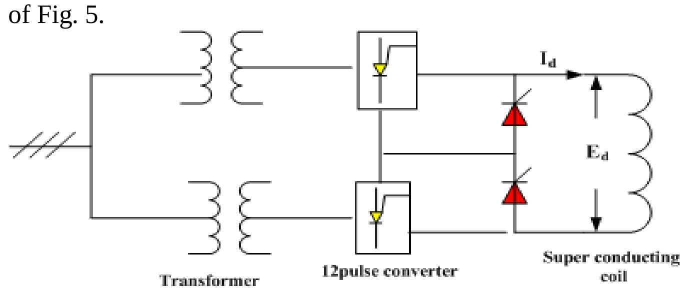

Figure 4. Equivalent circuit of SMES unit.

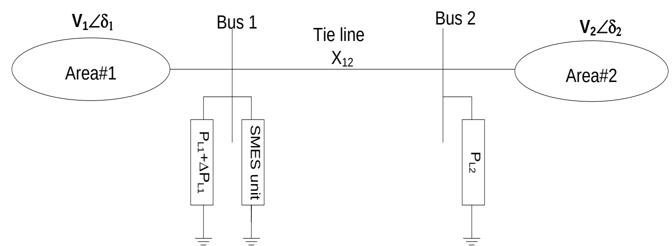

Figure 5. Single line diagram of the two-area power system with SMES unit.

In the proposed control strategy using SMES, when load demand is suddenly increases in a control area, the stored energy is almost released by the SMES through its power conversion system (PCS). As the governor control mechanism starts working to set the power to the new equilibrium condition, the SMES coil stores energy back to its nominal level. Similar action happens when there is a sudden decrease in load demand. In LFC operation, the DC voltage across the superconducting inductor E_d is continuously controlled depending on the sensed ACE signal or frequency deviation of the area which it connected [11, 14].

In the proposed installations of SMES where the tie-line power deviation signals $\Delta Ptie$ are presented, this effect can be achieved by the use of ACE in place of frequency deviation in the input of SMES control logic. With ACE input, ΔE_d is defined as:

$$\Delta E_d(s) = \frac{K_d}{1 + sT_d} ACE \quad (19)$$

Where:

K_d: The gain of the control loop.

T_d: The converter time delay.

The SMES inductor current deviation (ΔI_d) can be calculated as:

$$\Delta I_d = \frac{\Delta E_d}{SL} \quad (20)$$

Where L is coil inductance of SMES unit.

The deviation in the SMES unit inductor power flow ΔP_{SMES} is given as:

$$\Delta P_{SMES} = I_{do} * \Delta E_d + \Delta E_d * \Delta I_d \quad (21)$$

Where I_{do} is the initial value of inductor current. The block diagram represents the whole operation of SMES unit control system is illustrated in the Fig. 6.

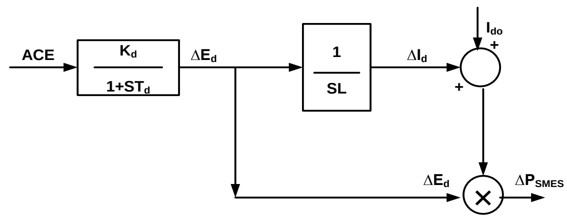

Figure 6. Block diagram of SMES unit control system.

V. SIMULATION RESULTS AND DISCUSSION.

1. Two-area interconnected power system with two thermal units

Two thermal area power system with equal power rating =2000 MW, with data given in Table. I are used in simulation [12].

TABLE I. TWO AREA POWER SYSTEM WITH THERMAL UNITS' DATA.

Device& Parameter	Area-1	Area-2
governor	Kg=1&Tg=0.08 sec	Kg=1&Tg=0.08 sec
turbine	Kt=1&Tt=0.3 sec	Kt=1&Tt=0.3 sec
Generator load	Kps=40 &Tps=20 sec	Kps=120 &Tps=20 sec
Frequency bias	Bf1=0.425p.u.MW/Hz	Bf1=0.425 p.u.MW/Hz
Synchronizing coefficient	T12=0.086	T21=-0.086
Speed regulation constant	R1=2.4 Hz p.u.MW	R2=2.4 Hz p.u.MW
PI controller	KP=1.007 &KI=1.083	KP= 1.00&KI=0.638

Small Load disturbance is applied to area-1; different control systems (PI, HVDC, and SMES) are applied to damp the oscillations at each area due to load disturbance.

Figure 7 shows the Matlab Simulink model of two area interconnected power system with AC tie line between two areas and PI controllers are used in each area to control the operation of governor unit help in damp out oscillations caused due to load disturbances.

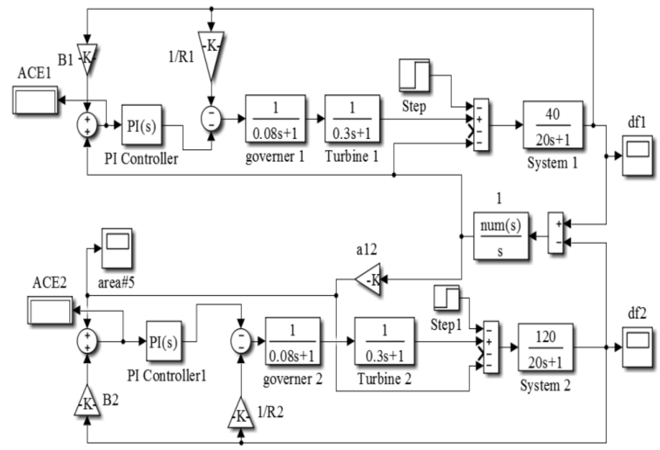

Figure 7. Matlab Simulink model of two areas interconnected power system with two thermal units.

Figure 8 shows the Matlab Simulink model of two area power system with AC-DC tie line between two areas, in which small power rating HVDC link (about 10% of rated power of area-1) is connected in parallel with AC tie line.

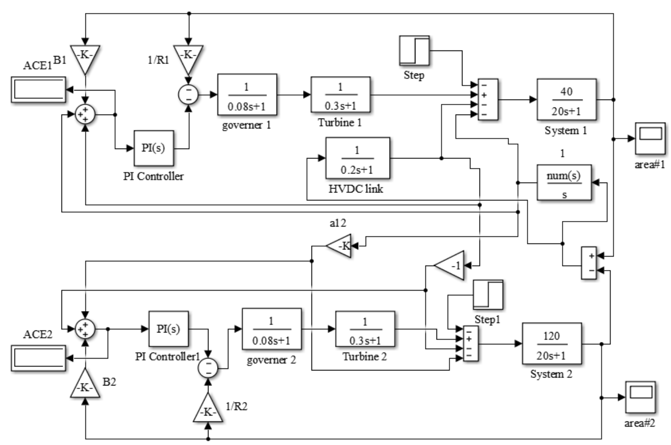

Figure 8. Matlab Simulink model of the proposed HVDC link between two areas interconnected power systems.

Figure 9 shows the Matlab Simulink model of two areas interconnected power system with SMES device with Tsmes=0.03 sec, L=2 H and I_{do}=5 KA [15] is connected at area-1.

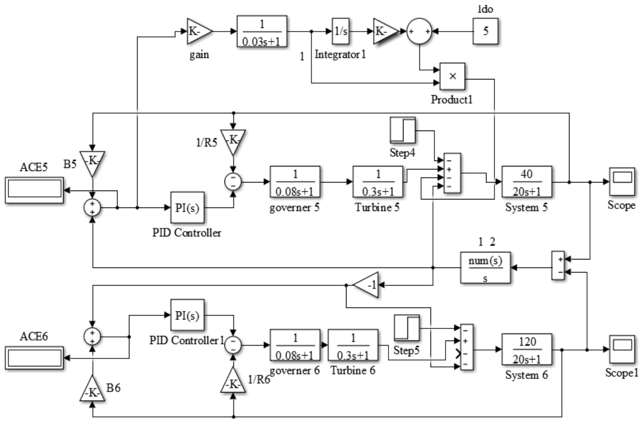

Figure 9. Matlab Simulink model of the proposed SMES unit connected at area-1 of two areas interconnected power systems.

Small disturbance in load about 10% in area-1 is represented in Matlab Simulink as a step signal applied at time t=2 sec. The frequency oscillations of each area, tie line power deviations between two areas are plotted with time in case of the three control strategies as shown in Figs.10, 11 and 12, respectively.

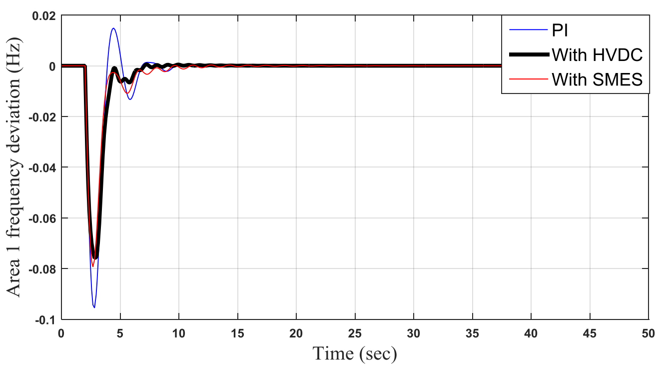

Figure 10. Frequency deviation response of area-1 due to 10% load disturbance at thermal area-1.

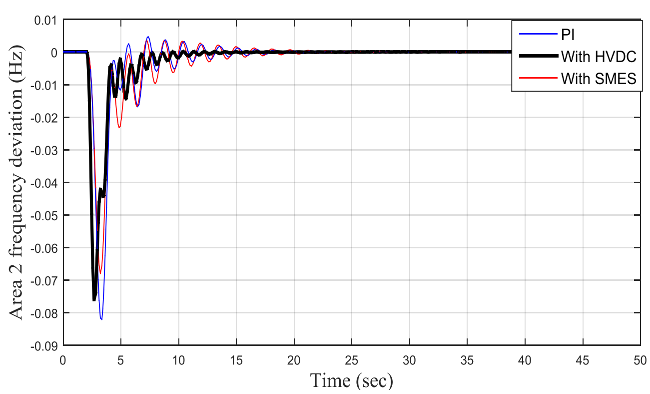

Figure 11.Frequency deviation response of area-2 due to 10% load disturbance at thermal area-1.

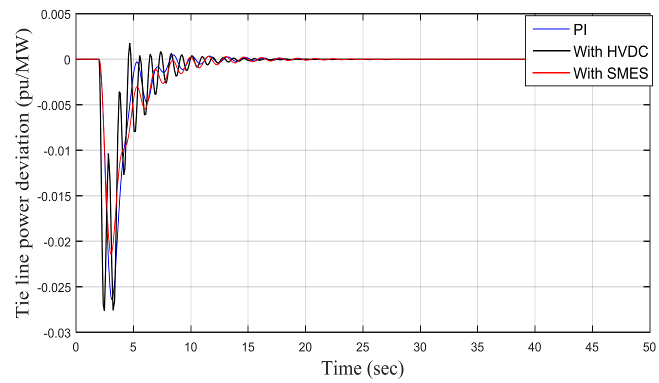

Figure 12.AC Tie line power deviation response due to 10% load disturbance at thermal area-1.

Table II gives the undershoot and settling time values of frequency deviation in the both areas, also the area control errors with the three control strategies.

TABLE II.PERFORMANCE SPECIFICATION DUE TO 10 % LOAD DISTURBANCE IN THERMAL AREA-1

Controller device	ΔF_1		ΔF_2		ΔP_{tie}		ACE	
	Undershoot(Hz)	Settling time (sec)	Undershoot(Hz)	Settling time(sec)	Undershoot(Hz)	Settling time(sec)	ACE_1*10 ^-7	ACE_2*10^-7
PI	-0.09	9	-0.082	19	-0.028	17	1.53	1.54
With SMES	-0.08	15	-0.068	22	-0.023	18	3.59	8.85
With HVDC	-0.07	7	-0.074	33	-0.026	16	.017	0.0265

From results of Figs. 10,11 and 12 and table (II) HVDC link is more appropriate controller between two areas interconnected power systems as a compared with SMES and PI controllers to restore system stability after load disturbance which occurs at any of two area at a small settling time. Simulation results shows that frequency deviation responses at each area with HVDC has small undershoot and low oscillations than using PI controller only and with SMES device. By controlling the power of HVDC link which connected in parallel with AC tie line, tie line power can be modulated .

2. Two area interconnected power system with thermal-hydraulic units

Figure13 shows the Matlab Simulink model of two areas interconnected power system with hydraulic unit in area-1 and thermal unit in area-2, with data given in Table.III [12].

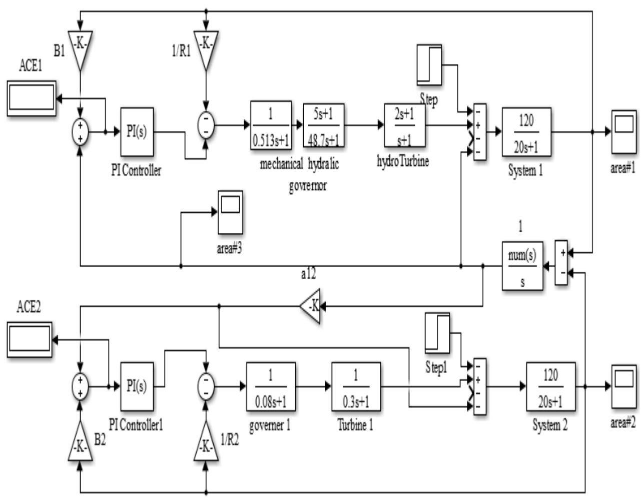

Figure 13. Matlab Simulink model of two areas interconnected power system with two hydraulic-thermal units.

TABLE III. Two areas power system with hydraulic-thermal units' data.

Device& Parameter	Area-1 (hydraulic)	Area-2 (thermal)
Governor	K_{gh}=1&T_{gh}=0.513sec T_2=5 sec&T_3=48.7 sec	K_g=1&T_g=0.08 sec
Turbine	T_w=2 sec	K_t=1&T_t=0.3 sec
Generator load	K_{ps}=120&T_{ps}=20 sec	K_{ps}=120&T_{ps}=20 sec
Frequency bias	B_{f1}=0.425p.u.MW/Hz	B_{f1}=0.425p.u.MW/Hz
Synchronizing coefficient	T_{12}=0.086	T_{21}=-0.086
Speed regulation constant	R_1=2.4 Hz p.u.MW	R_2=2.4 Hz p.u.MW
PI controller	K_P=1 &K_I=2.5	K_P= 1.5 &K_I=0.5

Small disturbance in load about 10% in hydraulic area-1 represented in Matlab Simulink as a step signal applied at time t=2 sec, The frequency oscillations of the hydraulic and thermal units and, tie line power deviations between two areas are plotted with time in case of the three control strategies as shown in Figs.14, 15 and 16, respectively.

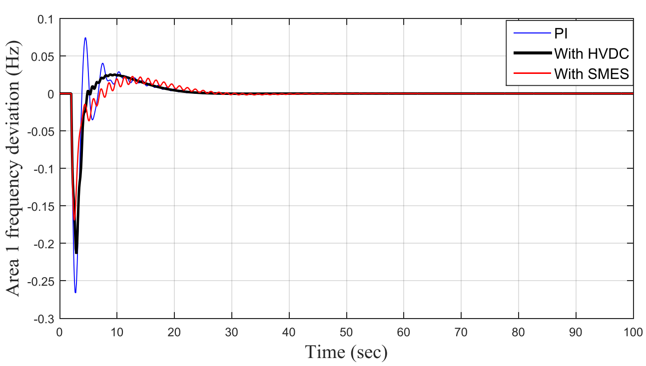

Figure 14.Frequency deviation response of hydraulic area-1 due to 10% load disturbance at hydraulic area-1.

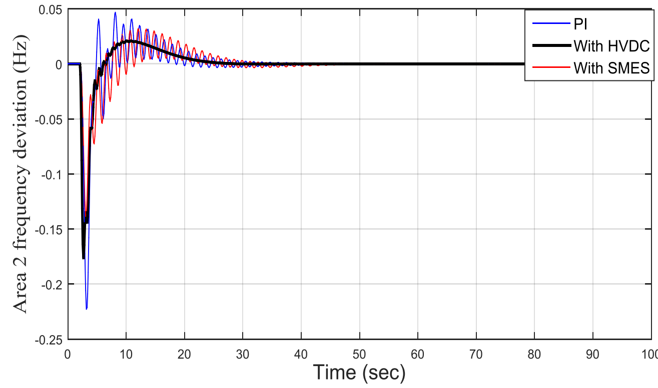

Figure 15. Frequency deviation response of thermal area-2 due to 10% load disturbance at hydraulic area-1

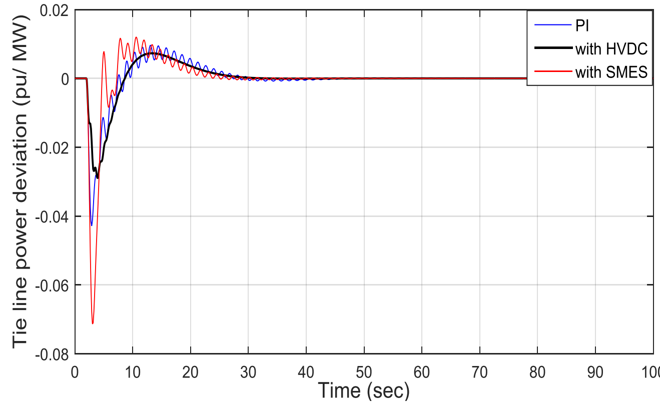

Figure 16. AC Tie line power deviation response due to 10% load disturbance at hydraulic area-1.

Undershoot and settling time values of frequency deviation in the hydraulic and thermal areas and the area control errors with the three control strategies are given in Table.IV.

TABLE IV. Performance specification due to 10 % load disturbance in hydraulic area-1

Controller device	ΔF_1		ΔF_2		ΔP_{tie}		ACE	
	Undershoot(Hz)	Settling time (sec)	Undershoot(Hz)	Settling time (sec)	Undershoot(Hz)	Settling time (sec)	ACE1*10 ^-10	ACE2*10 ^-10
PI	-0.265	30	-0.275	50	-0.07	45	3290	3080
With SMES	-0.175	35	-0.175	42	-0.06	38	371	219
With HVDC	-0.220	22	-0.175	24	-0.065	25	0.131	0.0081

From results of Figs. 13, 14 and 15 and Table. IV, HVDC link reduced settling time of frequency deviation response at area-1 from 35 sec in case of SMES to 22 sec. Also at area-2 from 42 sec to 24 sec. HVDC provide a responses with very small undershoot values than any other controller. ACE caused at each area can be reduced by using HVDC in parallel of AC tie line between two area thermal-hydraulic interconnected power systems

VI. CONCLUSIONS

In this paper, Mathematical equations for the area frequency deviation, deviation of tie line power and area control error in case of two area interconnected power system are obtained with HVDC connected in parallel with AC tie line power. SMES device can used to damp out the oscillations caused by the load variation at any of the two areas. In case of SMES unit, using of area control error (ACE) as a control signal gives a good dynamic performance than using of area frequency deviation. Simulation results show that; In case of two area interconnected power system with two thermal unit or thermal-hydraulic units, HVDC gives small undershoot values and fast settling time than SMES device when it is connected between two area interconnected power systems, also HVDC reduces area control error in the both areas. Dynamic simulation results show that HVDC is more reliable than SMES FACTS device in damping oscillation caused in the power system.

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