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LOAD FREQUENCY CONTROL USING PI$^+$ CONTROLLER IN A RESTRUCTURED POWER SYSTEM WITH HES AND SSSC UNITS

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ABSTRACT

This paper presents a sophisticated application of Hydrogen Energy Storage (HES) units and Static Synchronous Series Compensator (SSSC) coordinated with two-area interconnected restructured power system for the improvement of Load Frequency Control (LFC) loop. A new control strategy the Proportional and Integral plus (PI$^+$) controllers is designed using Krill Herd (KH) algorithm for solving LFC problem in power system. These controllers are implemented to achieve a faster restoration time in the output responses of the system when the system experiences with various step load perturbations. To stabilize the system for such load disturbance, comparative transient performance of two cases as (i) SSSC unit installed in series with tie-line, (iii) SSSC unit installed in series with tie-line in coordination with HES unit are analyzed. The second generation of FACTS controller namely SSSC unit can be installed in series with tie-line between any interconnected areas which can be applied to stabilize the area frequency oscillations by the high speed control action in regulating the power flow efficiently in the tie-line. More over the LFC loop with the coordinated control of HES and SSSC units have great improvement in the dynamic response and it reduces the control input requirements.

Keywords: Hydrogen Energy Storage, Krill Herd algorithm, Proportional and Integral plus (PI$^+$) controllers, Static Synchronous Series Compensator

1. INTRODUCTION

The traditional LFC two-area interconnected power system is modified to take into account the role of LFC in open market power system. Open transmission access and the evolving of more socialized companies for generation, transmission and distribution affects the formulation of LFC problem to accommodate new constraints associated with territorial functionality of each company. So the traditional LFC two-area interconnected power system is modified to take into account the effect of bilateral contracts on the dynamics (Mukta and Balwinder Singh Surjan). Based on the bilateral transactions, a distribution company (Disco) has the freedom to contract with any available generation company (Genco) in its own or another control area. These studies try to modify the conventional LFC system to take into account the effect of bilateral contracts on the dynamics and improve the dynamic and transient response of the system under various operating conditions (Donde *et al.*).The various combinations of contracts between each Disco and available Gencos on the other hand, each Genco can contract with various Discos. With the formation of Disco Participation Matrix (DPM) the visualization of contracts can be made easier.

The conventional controller are studied which gives the basic analysis of the LFC of the power system. The performances for Integral (I), Proportional-Integral (PI), Integral-Derivative (ID), and Proportional–Integral–Derivative (PID) controllers in LFC loop are practically the same from the viewpoint of dynamic responses (Lalit Chandra Saikia et al.). However, the proposed Proportional and Integral plus (PI$^+$) controllers provides much better response than the aforesaid controllers. In this study the PI$^+$ controller is designed using Krill Herd (KH) algorithm (Gandomi et al) and implemented for the two-area interconnected thermal reheat restructured power system.

The electromechanical oscillations in a power system can be effectively damped by fast acting Hydrogen Energy Storage (HES) with Fuel Cell unit (Valverde). Hydrogen is one of the promising alternatives that can be used as an energy carrier. The universality of hydrogen implies that it can replace other fuels for stationary generating units for power generation in various industries. Having all the advantages of fossil fuels, hydrogen is free of harmful emissions when used with dosed amount of oxygen, thus reducing the green house effect. The HES energy storage devices share the sudden changes in power requirement in the load. Thus, in a power system the instantaneous mismatch between supply and demand of real power for the sudden load changes can be reduced by the addition of active power sources with fast response. The recent advances in power electronics have led to the development of the Flexible Alternating Current Transmission System (FACTS) devices which can be adopted as one of the most effective ways to improve power system operation controllability and power transfer limits (Singh). The high speed control of SSSC can be coordinated with slow speed control of governor system for enhancing stabilization of area frequency oscillations effectively. Under these situations, the governor system may no longer be able to absorb the frequency fluctuations (Ngamroo). Static Synchronous

Series Compensator (SSSC) for the improvement of LFC loop of a power system and are capable of controlling the network condition in a very fast and economical manner and ensure to improve power system operation controllability and power transfer limits. In this study a PI^+ controllers are designed and implemented for LFC loop to control two-area reheat thermal interconnected deregulated power system with and without SSSC and HES unit. The coordinated control of SSSC and HES with the system can provide a better dynamic performance for all possible transactions f

2. DESIGN OF PROPORTIONAL-INTEGRAL PLUS (PI^+) CONTROLLERS

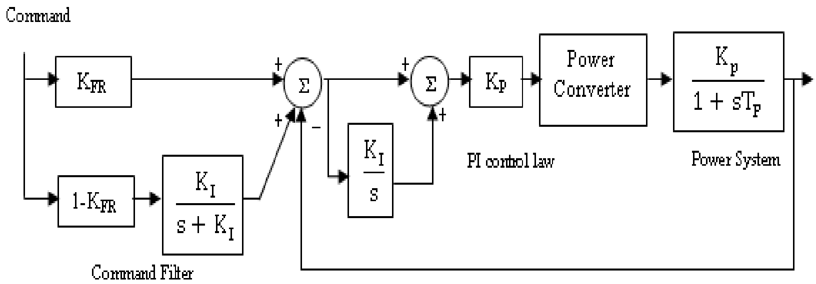

Figure-1: Block diagram of conventional PI^+ controller

In PI controller K_P provides stability and high frequency response and K_I ensures that the average error is driven to zero. The PI controller lacks a windup function to control the integral value during saturation. But PI^+ control uses a low pass filter on the command signal to limit the overshoot. Because of the overshoot, the integral gain in PI controllers is limited in magnitude. PI^+ control uses a low-pass filter on the command signal to remove overshoot. In this way, the integral gain can be raised to higher values. PI^+ controller is useful in LFC applications. The PI^+ controller block diagram is shown in Fig 1. The system has the PI controller with a command filter added. The degree to which a PI^+ controller filters the command signal is determined by the gain K_{FR}. When K_{FR} is 1, all filtering is removed and the controller is identical to a PI controller. Filtering is most severe when K_{FR} is zero. When K_{FR} is zero, command is filtered by $K_I/(s + K_I)$, which is a single-pole low-pass filter at the frequency K_I (in rad/sec). This case will allow the highest integral gain but also will most severely limit the controller command response. Typically, $K_{FR} = 0$ will allow an increase of almost three times in the integral gain but will reduce the bandwidth by about one-half when compared with $K_{FR} = 1$ (PI control). Finding the optimal value of K_{FR} depends on the application, but a value of 0.65 has been found to work in many applications. This value typically allows the integral gain to more than double while reducing the bandwidth by only 15%-20%. K_I as the frequency of the command low-pass filter because it is excellent at canceling the peaking caused by the integral gain. PI^+ control is that it uses the command filter to attenuate the peaking caused by PI. The peaking caused by K_I can be canceled by the attenuation of a low-pass filter with a break of K_I. In Fig.1 the control law for PI^+ controller is represented as

$$Control = K_P\left(command\left(K_{FR} + (1-K_{FR})\frac{K_I}{s+K_I}\right) - Feedback\right)\left(1+\frac{K_I}{s}\right) \tag{1}$$

The gains parameters of controllers and frequency stabilisers are so selected such that some degree of relative stability, damping of electro-mechanical oscillations, minimum overshoots (OSs) and undershoots (USs) and lesser settling time are achieved. In the present work ACE of the respective areas are considered as input to the controllers whereas the control inputs u_1 and u_2 are obtained with PI^+controller as

$$u_1 = K_{P_1}\left(ACE_1\left(K_{FR} + (1-K_{FR})\frac{K_{I1}}{s+K_{I1}}\right) - \Delta F_1\right)\left(1+\frac{K_{I1}}{s}\right) \tag{2}$$

$$u_2 = K_{P2}\left(ACE_2\left(K_{FR} + (1-K_{FR})\frac{K_{I2}}{s+K_{I2}}\right) - \Delta F_1\right)\left(1+\frac{K_{I2}}{s}\right) \tag{3}$$

In the present work an Integral Square Error (ISE) criterion is used to minimize the objective function which is defined as in Eqn (4). The control parameters of PI+ controller are tuned with KH algorithm (Gandomi).

$$J = \int_0^T \{(\beta_1\Delta f_1)^2 + (\beta_2\Delta f_2)^2 + (\Delta P_{tie12})^2\} \tag{4}$$

3. SYSTEM MODELLING FOR THE CONTROL DESIGN

The coordinated control actions of HES and SSSC units are found to be superior to the action of the governor system in terms of the response speed against the frequency fluctuations. The HES and SSSC units are tuned to suppress the peak value of frequency deviations quickly against the sudden load change, subsequently the governor system are actuated for compensating the steady state error of the frequency deviations. Fig.2 shows the Linearized reduction model of HES and SSSC units for the control design. An active power source to area 1 with gain constant K_{HES} and time constant T_{HES}. The SSSC is modeled as a tie- line power flow controller with a time constant T_{SSSC}.. Then the state equation of the system represented by Fig. 2 becomes

$$\begin{bmatrix} \Delta \dot{F}_1 \\ \Delta \dot{P}_{T12} \\ \Delta \dot{F}_2 \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{T_{p1}} & -\dfrac{K_{p1}}{T_{p1}} & 0 \\ 2\pi T_{12} & 0 & -2\pi T_{12} \\ 0 & \dfrac{a_{12}\,k_{p2}}{T_{p2}} & -\dfrac{1}{T_{p2}} \end{bmatrix} \begin{bmatrix} \Delta F_1 \\ \Delta P_{T12} \\ \Delta F_2 \end{bmatrix} + \begin{bmatrix} \dfrac{k_{p1}}{T_{p1}} \\ 0 \\ 0 \end{bmatrix} \left[\Delta P_{HES}\right] \tag{5}$$

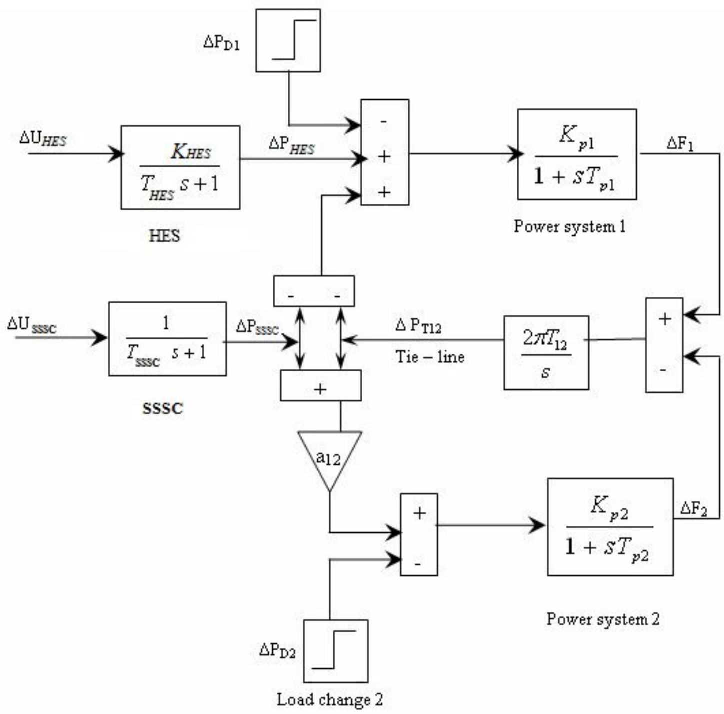

Figure-2: Linearized reduction model for the test system with HES and SSSC units

3.1 Control design of HES unit with Fuel cell

The design process starts from the reduction of two area system into one area which represents the Inertia centre mode of the overall system. The controller of HES is designed for the equivalent one area system to reduce the frequency deviation of inertia centre. The equivalent system is derived by assuming the synchronizing coefficient T_{12} to be large. From the state equation of $\Delta \dot{P}_{T12}$ in Eq (5)

$$\frac{\Delta \dot{P}_{T12}}{2\pi T_{12}} = \Delta F_1 - \Delta F_2 \tag{6}$$

Setting the value of T_{12} in Eq (6) to be infinity yields $\Delta F_1 = \Delta F_2$.

$$\Delta \dot{F} = \frac{\left(-\dfrac{1}{k_{p1}} - \dfrac{1}{k_{p2}a_{12}}\right)}{\left(\dfrac{T_{p1}}{k_{p1}} + \dfrac{T_{p2}}{k_{p2}a_{12}}\right)}\Delta F + \frac{1}{\left(\dfrac{T_{p1}}{k_{p1}} + \dfrac{T_{p2}}{k_{p2}a_{12}}\right)}\Delta P_{HES} + C\Delta P_D \tag{7}$$

Where ΔP_D is the load change in this system and the control $\Delta P_{HES} = -K_{HES}\,\Delta F$ is applied then.

$$\Delta F = \frac{C}{s + A + K_{HES} \ B} \Delta P_D \quad (8)$$

Where $A = \left(-\frac{1}{k_{p1}} - \frac{1}{k_{p2} a_{12}} \right) \bigg/ \left(\frac{T_{p1}}{k_{p1}} + \frac{T_{p2}}{k_{p2} a_{12}} \right)$ and $B = \frac{1}{\left[\frac{T_{p1}}{K_{p1}} + \frac{T_{p2}}{K_{p2} a_{12}} \right]}$

where C- is the proportionality constant between change in frequency and change in load demand. Since the control action of HES unit is to suppress the deviation of the frequency quickly against the sudden change of $\Delta P_{D,}$ the percent reduction of the final value after applying a step change ΔP_D can be given as a control specification. In Eqn (10) the final values with K_{HES} = 0 and with $K_{HES} \neq 0$ are C/A and C / (A+K_{HES} B) respectively therefore the percentage reduction is represented by

$$C/(A + K_{HES} \ B) \Big/ (C / A) = R/100 \quad (9)$$

For a given R, the control gain of HES is calculated as

$$K_{HES} = \frac{A}{BR} (100 - R) \quad (10)$$

3.2 Control design of SSSC unit

The controller for the SSSC is design to enhance the damping of the inter-area mode. In order to extract the inter-area mode from the system Eqn (5), the concept of overlapping decompositions is applied. First, the state variables of the system Eqn (6) are classified into three groups, i.e. $x_1 = [\Delta F_1], x_2 = [\Delta P_{T12}], x_3 = [\Delta F_2]$. next, the system Eqn (6) is decomposed into two decoupled subsystems. Where the state variable ΔP_{T12} is duplicated included in both subsystems, which is the reason that this process is called overlapping decompositions. Then, one subsystem which preserves the inter-area mode is represented by.

$$\begin{bmatrix} \Delta \dot{F}_1 \\ \Delta \dot{P}_{T12} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_{p1}} & \frac{-Kp_1}{T_{p1}} \\ 2\pi \ T_{12} & 0 \end{bmatrix} \begin{bmatrix} \Delta F_1 \\ \Delta P_{T12} \end{bmatrix} + \begin{bmatrix} \frac{-Kp_1}{T_{p1}} \\ 0 \end{bmatrix} [\Delta P_{TCPS}] \quad (11)$$

It has been proved that the stability of original system is guaranteed by stabilizing every subsystem. Since the system Eqn (11) is the second order oscillation system, the percentage overshoot Mp (new) can be specified for the control design. Therefore the control scheme of TCPS is designed to enhance the stability of the system Eqn (11) by eigenvalue assignment method. Here let the conjugate eigenvalue pair of the system Eqn (11) be $\alpha \pm j\beta$, which corresponds to the inter-area mode. The control purpose of the TCPS is to damp the peak value of frequency deviation in area 1 after a sudden change in the load demand. Since the system Eqn (11) is the second order oscillation system, the percentage overshoot Mp (new) can be specified for the control design. Mp (new) is given as a function of the damping ratio by

$$M_{p(new)} = e^{(-\pi \delta / \sqrt{1-\delta^2})} \quad (12)$$

The real and imaginary parts of eigenvalue after the control are expressed by

$$\alpha_s = \delta \omega_n \quad (13)$$

$$\beta_s = \omega_n \sqrt{1 - \delta^2} \quad (14)$$

Where ω_n is the undamped natural frequency, by specifying Mp and assuming $\beta_s = \beta$, the desired pair of eigenvalue is fixed. As a result, the eigenvalue assignment method derives to feed back scheme as

$$\Delta P_{TCPS} = -k_1 \Delta F_1 - k_2 \Delta P_{T12} \quad (15)$$

The Linearized model of a two-area interconnected reheat thermal power system in deregulated environment is shown in Fig.3 after incorporating either with SSSC unit or HES and SSSC units.

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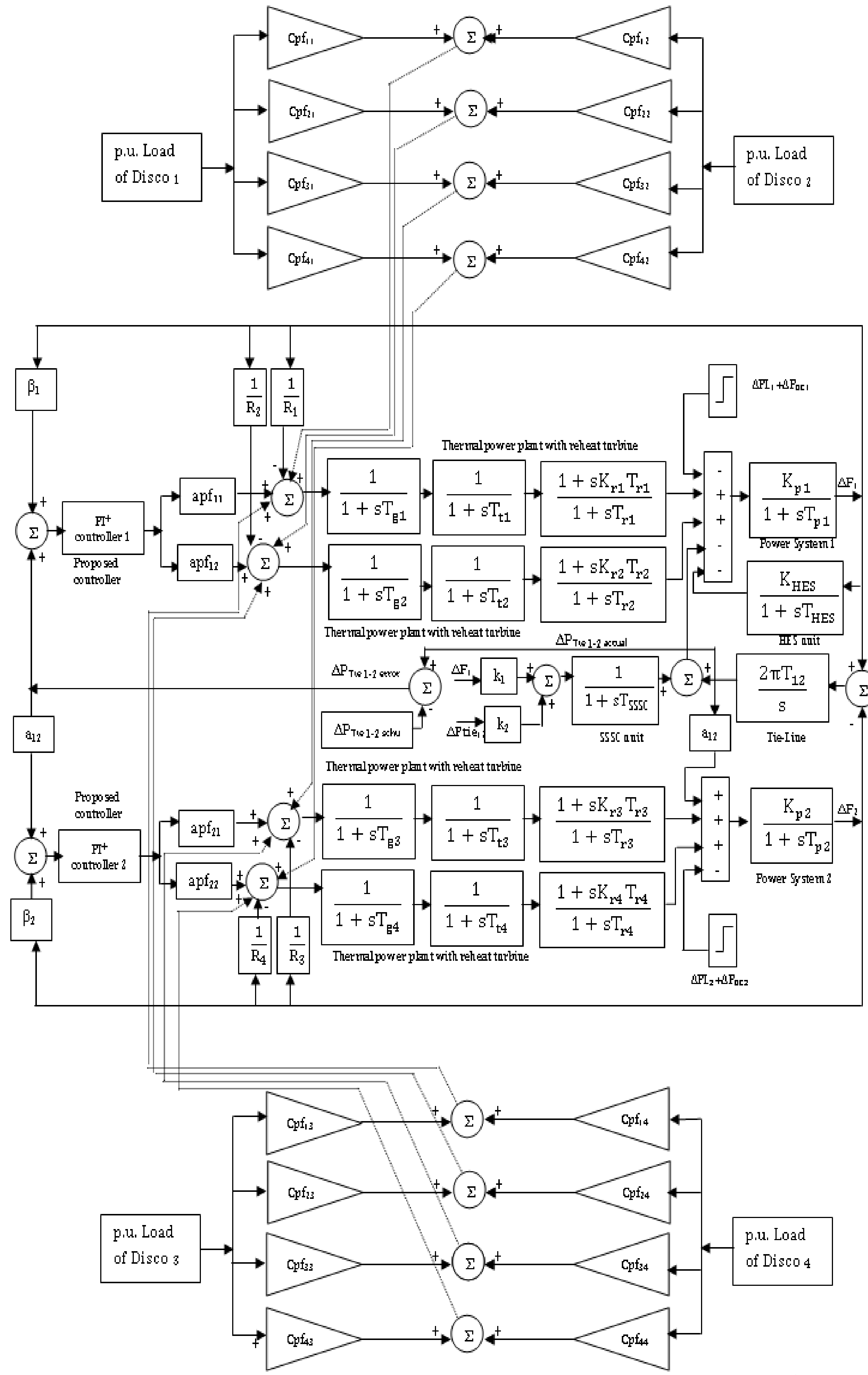

Figure-3: Linearized model of a two-area Thermal reheat interconnected power system using PI+ controller in a restructured environment with HES and SSSC units.

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4. RESULTS AND DISCUSSION

Krill Herd (KH) algorithm was adopted for optimizing the control parameters of PI+ controller for two the area interconnected thermal power system without and with SSSC only and the coordinated control action of the HES and SSSC units. In this study the active power model of SSSC controllers is fitted in the tie-line near area1 to examine its effect on the power system performance. Then HES unit is installed in area 1 and coordinated with SSSC controller for LFC to study the dynamic performance of test system for different possible transactions. In poolco based scenario, Gencos participate only in load following control of their areas. Assume that the load change occurs only in area 1. Thus, the load is demanded only by $Disco_1$and $Disco_2$. Let the value of this load demand be 0.2 pu.MW and 0.1 pu.MW $Disco_1$ and $Disco_2$ respectively, .i.e. ΔP_{L1}= 0.2 pu.MW, $\Delta P_{L\ 2}$= 0.1 pu.MW, $\Delta P_{L3} = \Delta P_{L4}$= 0.0. Also, it is assumed that a case of Poolco based contracts between Discos and available Gencos are simulated based on the following Disco Participation Matrix as follows (16).

$$DPM1 = \begin{bmatrix} 0.5 & 0.5 & 0.0 & 0.0 \\ 0.5 & 0.5 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix} \qquad (16)$$

The optimum gain values of the PI^+ controllers ($K_{pi,}$ K_{Ii}) in LFC loop for the test system without and with HES and SSSC unit are listed in Table 1 and 2. The proposed controllers are implemented for the test system and comparative dynamic response is shown in Fig 4. From the simulation results, it can be observed that the oscillations in area frequencies, tie-line power deviation and control input requirements have decreases to a considerable extent for the system with use of HES and SSSC unit. It can be observed that the test system with HES coordinated SSSC unit have not only reduces the cost function but also ensure better stability, as they possesses less over/under shoot and faster settling time. Thus HES unit coordinated with SSSC unit improves inertia mode and inter area mode oscillations effectively.

Table-1: Optimal PI^+ controller gain values for two-area power system with SSSC unit for corresponding Change in Load demand

Test system	PI^+controller gain values in Area 1 With K_{FR} =0.65		PI^+ controller gain values in Area 2 With K_{FR} =0.65		Load demand in pu.MW				uncontracted load demand in pu MW	
	K_{P1}	K_{I2}	K_{P2}	K_{I2}	$Disco_1$	$Disco_2$	$Disco_3$	$Disco_4$	Area 1	Area 2
Case 1	0.342	0.575	0.198	0.258	0.2	0.1	0.0	0.0	0.0	0.0
Case 2	0.355	0.467	0.251	0.264	0.2	0.1	0.0	0.0	0.1	0.0
Case 3	0.412	0.501	0.297	0.267	0.2	0.1	0.0	0.0	0.0	0.1
Case 4	0.467	0.468	0.308	0.271	0.2	0.1	0.0	0.0	0.1	0.1
Case 5	0.404	0.522	0.311	0.267	0.15	0.15	0.15	0.15	0.0	0.0
Case 6	0.354	0.587	0.195	0.338	0.15	0.15	0.15	0.15	0.15	0.0
Case 7	0.397	0.617	0.197	0.349	0.15	0.15	0.15	0.15	0.0	0.15
Case 8	0.398	0.631	0.301	0.264	0.15	0.15	0.15	0.15	0.15	0.15
Case 9	0.406	0.654	0.343	0.352	0.1	0.2	0.1	0.2	0.0	0.0
Case 10	0.434	0.679	0.249	0.367	0.1	0.2	0.1	0.2	0.2	0.0
Case 11	0.421	0.645	0.317	0.308	0.1	0.2	0.1	0.2	0.0	0.2
Case 12	0.444	0.643	0.324	0.369	0.1	0.2	0.1	0.2	0.2	0.2

Table 2: Optimal PI[+] controller gain values for two-area power system with HES and SSSC unit for corresponding Change in Load demand

Test system	PI[+] controller gain values in Area 1 With K_{FR} =0.65		PI[+] controller gain values in Area 2 With K_{FR} =0.65		Load demand in pu.MW				Uncontracted load demand in pu MW	
	K_{P1}	K_{I2}	K_{P2}	K_{I2}	$Disco_1$	$Disco_2$	$Disco_3$	$Disco_4$	Area 1	Area 2
Case 1	0.275	0.613	0.157	0.311	0.2	0.1	0.0	0.0	0.0	0.0
Case 2	0.311	0.508	0.197	0.336	0.2	0.1	0.0	0.0	0.1	0.0
Case 3	0.357	0.555	0.235	0.343	0.2	0.1	0.0	0.0	0.0	0.1
Case 4	0.378	0.515	0.273	0.358	0.2	0.1	0.0	0.0	0.1	0.1
Case 5	0.365	0.588	0.297	0.337	0.15	0.15	0.15	0.15	0.0	0.0
Case 6	0.279	0.649	0.167	0.386	0.15	0.15	0.15	0.15	0.15	0.0
Case 7	0.327	0.685	0.168	0.419	0.15	0.15	0.15	0.15	0.0	0.15
Case 8	0.328	0.701	0.246	0.367	0.15	0.15	0.15	0.15	0.15	0.15
Case 9	0.341	0.705	0.258	0.462	0.1	0.2	0.1	0.2	0.0	0.0
Case 10	0.367	0.764	0.192	0.473	0.1	0.2	0.1	0.2	0.2	0.0
Case 11	0.388	0.767	0.286	0.397	0.1	0.2	0.1	0.2	0.0	0.2
Case 12	0.371	0.757	0.303	0.426	0.1	0.2	0.1	0.2	0.2	0.2

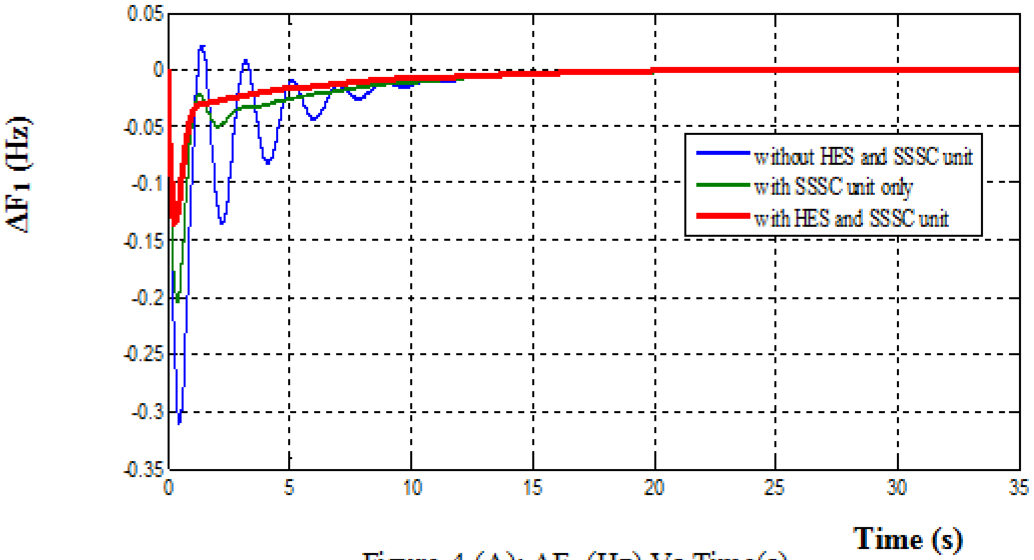

Figure-4 (A): ΔF_1 (Hz) Vs Time(s)

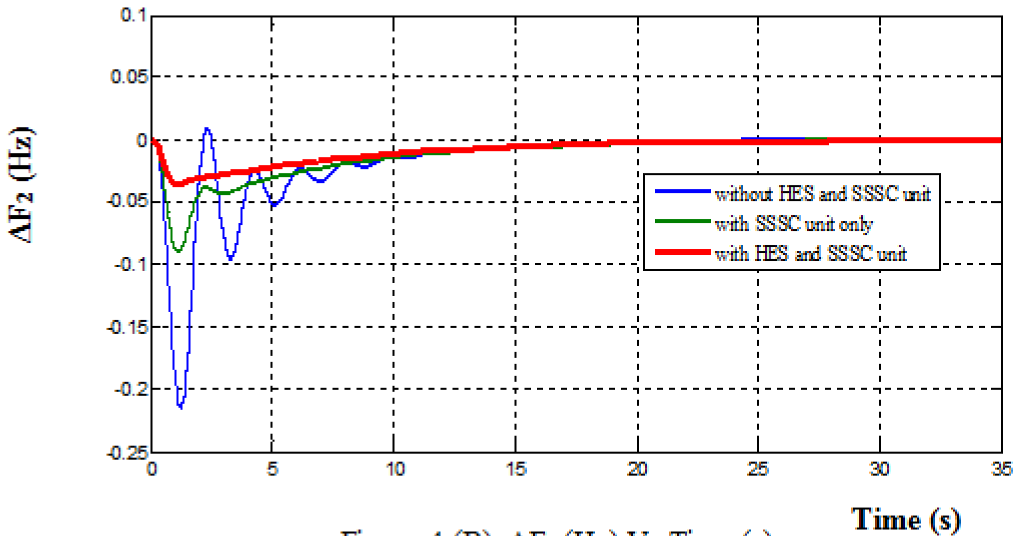

Figure-4 (B): ΔF_2 (Hz) Vs Time (s)

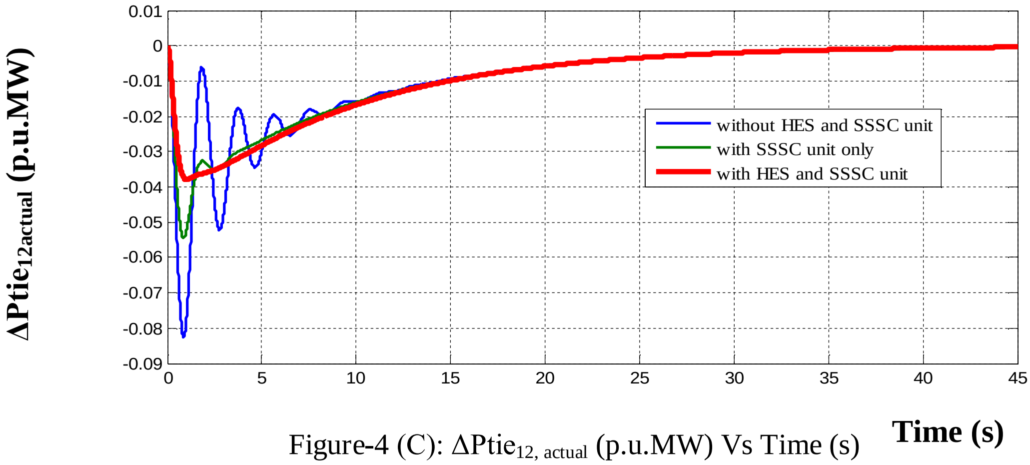

Figure-4 (C): $\Delta Ptie_{12,\ actual}$ (p.u.MW) Vs Time (s)

Figure-4: Dynamic responses of the frequency deviations and tie- line power deviations for a two area power system without and with HES and SSSC unit using PI^{+} controllers (Poolco based transactions, case-1)

5. CONCLUSION

The optimal parameters of the proposed PI^{+} controllers are tuned with Krill Herd algorithm for the test system with and without HES and SSSC unit. The results demonstrate that KH algorithm is able to reach the optimal solution irrespective of the large variation with a faster convergence rate. A control strategy has been proposed to adjust the voltage of SSSC which in turn controls the inter-area tie- line power flow. Simulation results reveal that the first peak frequency deviation of both areas and tie-line power oscillations following sudden load disturbances in either of the areas can be suppressed a controlling the series voltage of SSSC. Moreover, the tie-line power flow control by an SSSC units are found to be efficient and effective for Improving the dynamic performance of load frequency control of inter connected power system. For an overload condition for a short time period because of nature of HES unit the extremely faster response is obtained with HES unit which has a reduced charging and discharging period and hence they are very well suitable. From this it is evident that HES contributes a lot in promoting the efficiency of overall generation control through the effect of the use in load levelling and the assurance of LFC capacity after overload characteristic and quick responsiveness. It should be noted that the design concept of damping the inertia mode and inter-area mode, the coordinated control is effective enough to suppress the frequency deviation of two area system simultaneously.

6. ACKNOWLEDGEMENT

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REFERENCES

1. Donde, V., Pai, M.A. and Hiskens, I.A. (2001), ‘Simulation and optimization in an AGC system after deregulation, IEEE transactions on power systems, 16(3): 481-489.
2. Gandomi, A.H. and Alavi, A.H. (2012), ‘Krill herd: a new bio-inspired optimization algorithm’, Communications in Nonlinear Science and Numerical Simulation, 17(12): .4831-4845.
3. Lalit Chandra Saikia, Nanda, J., and Mishra, S. (2011), ‘Performance comparison of several classical controllers in AGC for multi-area interconnected thermal system’ International Journal Electrical Power and Energy Systems, 33: 394-401.
4. Mukta and Balwinder Singh Surjan. (2013), ‘Load Frequency Control of Interconnected Power System in Deregulated Environment: A Literature Review’, International Journal of Engineering and Advanced Technology, 2(3): 435-441.
5. Ngamroo, I., Tippayachai, J. and Dechanupaprittha, S., (2006), ‘Robust decentralised frequency stabilisers design of static synchronous series compensators by taking system uncertainties into consideration’, International Journal of Electrical Power and Energy Systems, 28(8): 513-524.
6. Singh, B., (2011), ‘Applications of FACTS controllers in power systems for enhance the power system stability: a state-of-the-art’, International Journal of Reviews in Computing, 6: 40-69.
7. Valverde, L., Rosa, F. and Bordons, C. (2013), ‘Design, planning and management of a hydrogen-based microgrid’, IEEE Transactions on industrial informatics, .9 (3): 1398-1404.