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Proportional-Integral with filtered Integral mode Controller using Krill Herd (KH) algorithm in a Restructured Power System with HES and IPFC Units

K.Chandrasekar [1], B. Paramasivam [2] and I.A. Chidambaram [3]
[1] *Lecturer, Department of EEE, Government Polytechnic College, Ariyalur, Tamilnadu, India*
[2] *Assistant Professor, Department of EEE, Government College of Engineering, Bodinayakkanur, Tamilnadu, India*
[3] *Professors, Department of Electrical Engineering, Annamalai University, Annamalainagar, Tamilnadu, India,*

Abstract: *This paper presents the design methodology using Proportional and Integral plus (PI^+) controllers and Proportional-Integral (PI) with Filtered Integral (PIFI) mode controller for the Automatic Generation Control (AGC) of a restructured power system. The control parameters of PIFI and PI^+ controllers are optimized employing Krill Herd (KH) algorithm to achieve the optimal transient response of the two-area thermal reheat interconnected power system under various possible transactions in the restructured environment. The proposed controller, a filter was added to the integral term which decouples the effective frequency ranges between the integral and proportional terms without degradation of the integral action. It produces a phase lead in a certain frequency range without having a derivative term, enhancing the control performances and stability robustness. In this study, a sophisticate application of Hydrogen Energy Storage (HES) coordinated with Interline Power Flow Controller (IPFC) is adopted for the improvement of AGC loop of the power system. The IPFC unit is to stabilize the frequency oscillations of the inter-area mode in the interconnected power system by the dynamic control of tie-line power flow and HES unit share the sudden changes in power requirement and to maintain the power quality of distributed power resources. From the simulations results, it can be observed that the proposed controllers are implemented for AGC loop of a test system with the incorporation of IPFC and HES units to enhance the total transfer capability and decrease the line congestion and to ensure power system restoration in order to provide good margin of stability.*

Keywords: *AGC, PI^+ controller, PIFI controller, HES, IPFC, Krill Herd algorithm and Power System Restoration Indices.*

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I. Introduction

The main objective of a power system utility is to maintain continuous supply of power with an acceptable quality to all the consumers in the system. The system will be in equilibrium, when there is a balance between the power demand and the power generated [1]. Large variation of frequency from the scheduled value causes instability to the power system unit. AGC plays an important role for power system stabilizer, to maintain the system frequency and tie-line power within acceptable limits with the variation of load demands. AGC monitors the system frequency and tie-line flows, calculates the net change in the generation required according to the change in demand and changes the set position of the generators within the area so as to keep the time average of the ACE (Area Control Error) at a low value. As the ACE is adjusted to zero by the AGC, both frequency and tie-line power errors will become zero [2]. The electric power industry has been undergoing reforms from vertical integrated utility (VIU) to competitive deregulated markets. Generation companies (Genco), distribution companies (Disco), transmission companies (Transco) and independent system operator (ISO) are all the major market players in a deregulated market structure. In a large power system network having so many Gencos and Discos and also each Gencos and Discos having different contract with each other for power transactions [3-6]. At the same time ISO provide a certain number of ancillary services for provide the smooth operation of deregulated markets. Due to the complexity of the modern power system, the system oscillation exposed to any electrical disturbance may spread to wide interconnected system of different control area. It creates undesirable disturbance, which cause the instability that will lead to complete system black out. For mitigation or to control over the above-discussed problem different controlling aspects of LFC are developed and successfully employed in the power system.

The conventional controller are studied which gives the basic analysis of the AGC of the power system. The performances for Integral (I), Proportional–Integral (PI), Integral–Derivative (ID) and Proportional–Integral–Derivative (PID) controllers in AGC are practically the same from the viewpoint of dynamic responses

[7, 8]. However, the proposed Proportional and Integral plus (PI^+) and Proportional-Integral (PI) controller with Filtered Integral (PIFI) and controllers provides much better response than the aforesaid controllers. The controller parameters plays a vital role for its performance, thus it should be tuned properly with suitable optimization techniques.

Many evolutionary heuristic algorithms have been proposed in the area of AGC for better performance analysis by the researchers over past two decades such as Differential Evolution (DE) [9], Particle Swarm Optimisation (PSO) [10], Genetic Algorithm (GA) [11], Craziness-based PSO (CRPSO) [12] and Bacterial Foraging Optimization (BFO) algorithm [13] etc. However, they suffer from local optimisation problem, required long simulation time, complex algorithm etc. From literature survey the enhancement of power system performance not only depends on the control structure but also on the well-tuned controllers. Therefore, modern evolutionary methods such as Krill Herd (KH) algorithm which is a novel swarm intelligent algorithm inspired by the herding behavior of the krill swarms. In the algorithm, three main factors define the position of the krill individuals that are movement induced by the presence of other individuals, foraging activity, and random diffusion [14-16]. In this study the proposed controllers are designed using KH algorithm and implemented for the two-area interconnected thermal reheat restructured power system.

In an interconnected power system area, inter area oscillations are quite common, which results in severe frequency deviations. Flexible AC Transmission System (FACTS) devices are also used to damp out these oscillations. Also, energy storage devices improve the power transfer capability and power management of the interconnected power system [17, 18]. In this study the concept of AGC in two-area reheat power system having coordinated control action with Hydrogen Energy Storage (HES) and Interline Power Flow Controller (IPFC) units are capable of controlling the network performance in a very fast manner and to improve power transfer limits in order to have a better restoration. This paper proposes computation of Power System Restoration (PSR) Indices based on the Automatic Generation Control (AGC) assessment of interconnected restructured power system without and with IPFC and HES units. The PSR indices are calculated based on the settling time and peak over shoot concept of the dynamic output responses of the system and the control input deviations of each area for different types of possible transactions and the necessary remedial measures to be adopted are also suggested.

II. Modeling of IPFC and HES devices.

2.1 Inter-line Power Flow Controller

The active power controller of IPFC has a structure of the Lead-Lag compensator with output signal $\Delta P_{ref.}$ In this study the dynamic characteristics of IPFC is modeled as the first order controller with time constant T_{IPFC}. It is to be noted that the injected power deviations of IPFC unit, ΔP_{IPFC} acting positively on the area 1 reacts negatively on the area 2. Therefore ΔP_{IPFC} flow into both area with different signs (+, -) simultaneously. The commonly used Lead-Lag structure is chosen in this study as IPFC based supplementary damping controller as shown in Fig 1. The structures consist of a gain block, a washout block and two-stage phase compensation block. The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and output signals. The input signals associated with oscillations is passed unchanged would modify the output. The input signal of the proposed IPFC-based controller is frequency deviations Δf and tie- line power deviations and the output is the change in control vector $\Delta P_{IPFC.}$ From the view point of the washout function the value of washout time constant is not critical in Lead-Lag structured controllers and may be in the range 1 to 20 seconds.

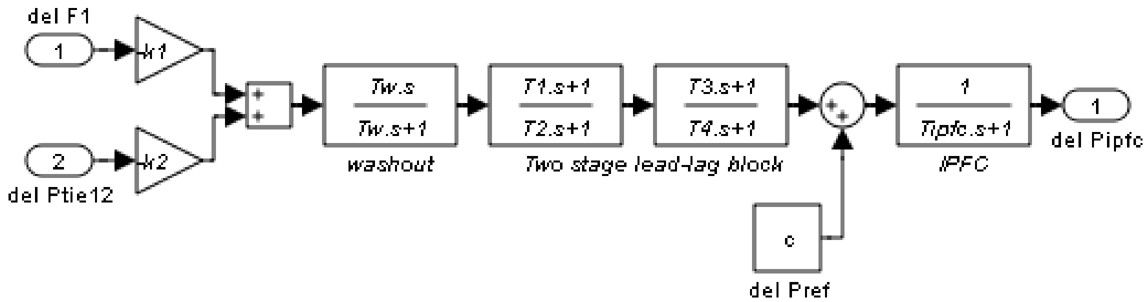

Fig.1 Structure of IPFC-based damping controller

2.2 Hydrogen Energy Storage (HES) devices

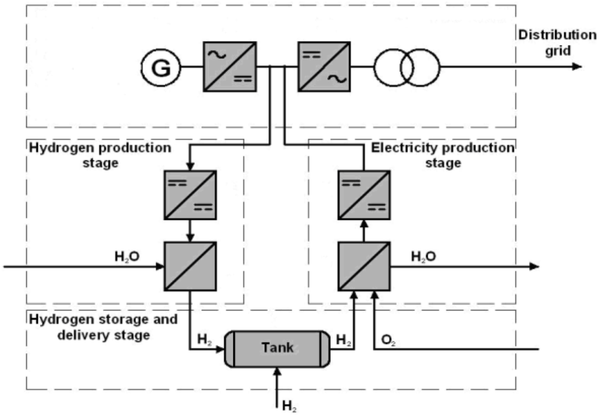

Fig 2 Block diagram of the Hydrogen Energy Storage (HES) unit

The essential elements of a hydrogen energy storage system comprise an electrolyzer unit which converts electrical energy input into hydrogen by decomposing water molecules, the hydrogen storage system itself and a hydrogen energy conversion system which converts the stored chemical energy in the hydrogen back to electrical energy as shown in Fig 2 [19, 20].

The transfer function of the Aqua Electrolyzer can be expressed as first order lag

$$G_{AE}(s) = \frac{K_{AE}}{1+sT_{AE}} \quad (1)$$

The transfer function of Fuel Cell (FC) can be given by a simple linear equation as

$$G_{FC}(s) = \frac{K_{FC}}{1+sT_{FC}} \quad (2)$$

The overall transfer function of hydrogen Energy storage unit has can be

$$G_{HES}(s) = \frac{K_{HES}}{1+sT_{HES}} = \frac{K_{AE}}{1+sT_{AE}} * \frac{K_{FC}}{1+sT_{FC}} \quad (3)$$

III. Design of proposed controllers

3.1 Proportional-Integral plus (PI^+) controller

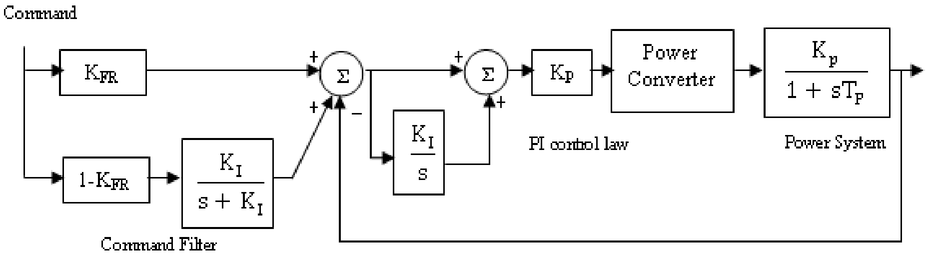

Fig.3 Block diagram for PI^+ controller

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. The Proportional and Integral plus (PI^+) controller is an enhancement to PI. 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. The Fig 3 shows block diagram of PI^+ controller and the control law for PI^+ controller is represented as (4)

$$Control = K_P\left(command\left(K_{FR} + (1-K_{FR})\frac{K_I}{s+K_I}\right) - Feedback\right)\left(1+\frac{K_I}{s}\right) \quad (4)$$

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 and the control inputs u_1 and u_2 are obtained with PI^+ controller as Eqn (5) and (6). Integral Square Error (ISE) criterion is used to minimize the objective function which is defined as in Eqn (9).

$$u_1 = K_{P1}\left(ACE_1\left(K_{FR} + (1-K_{FR})\frac{K_{I1}}{s+K_{I1}}\right) - \Delta F_1\right)\left(1+\frac{K_{I1}}{s}\right) \tag{5}$$

$$u_2 = K_{P2}\left(ACE_2\left(K_{FR} + (1-K_{FR})\frac{K_{I2}}{s+K_{I2}}\right) - \Delta F_1\right)\left(1+\frac{K_{I2}}{s}\right) \tag{6}$$

3.2 Proportional-Integral (PI) with Filtered Integral (PIFI) mode Controller

The block diagram of Proportional-Integral (PI) with Filtered Integral (PIFI) mode Controller is shown in Fig 4. Integral action is almost always included in process control systems to eliminate steady-state offset without uncertain process gain. The open-loop pole, however, at the origin of the integral term causes some problems such as integral windup. Various methods to solve these problems were studied. For better control performance and robustness, a filter was added to the integral term, which decouples the effective frequency ranges between the integral and proportional terms without degradation of the integral action. It produces a phase lead in a certain frequency range without having a derivative term, enhancing the control performances and stability robustness. Based on the internal model control method or the direct synthesis method, tuning rules for the proposed controller are given. The control inputs u_1 and u_2 are obtained with PIFI controller as Eqn (7) and (8). In the present work Integral Squared Error (ISE) criterion is used to minimize the objective function which is defined as in Eqn (9).

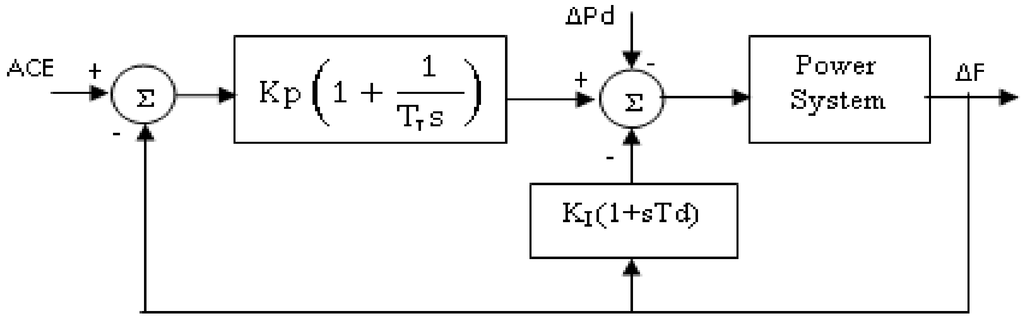

Fig.4 Block diagram for PIFI controller

$$u_1 = (ACE_1 - \Delta F_1)\left(K_{P1}\left(1+\frac{1}{T_{i1}s}\right)\right) - K_{P1}\left(1+\frac{1}{T_{i1}s}\right) - \Delta P_{d1} \tag{7}$$

$$u_2 = (ACE_2 - \Delta F_2)\left(K_{P2}\left(1+\frac{1}{T_{i2}s}\right)\right) - K_{P2}\left(1+\frac{1}{T_{i2}s}\right) - \Delta P_{d2} \tag{8}$$

$$J = \int_0^T \{(\beta_1 \Delta f_1)^2 + (\beta_2 \Delta f_2)^2 + (\Delta P_{tie\,12})^2\} \tag{9}$$

The proposed controller parameters are optimized using Krill Herd (KH) algorithm for a two-area thermal reheat interconnected power system in a restructured environment without and with IPFC and HES units is shown in Fig 5. The relative simplicity of this controller is a successful approach towards the zero steady state error in the frequency of the system. With these optimized gain values the performance of the system is analyzed and various PSR indices are computed.

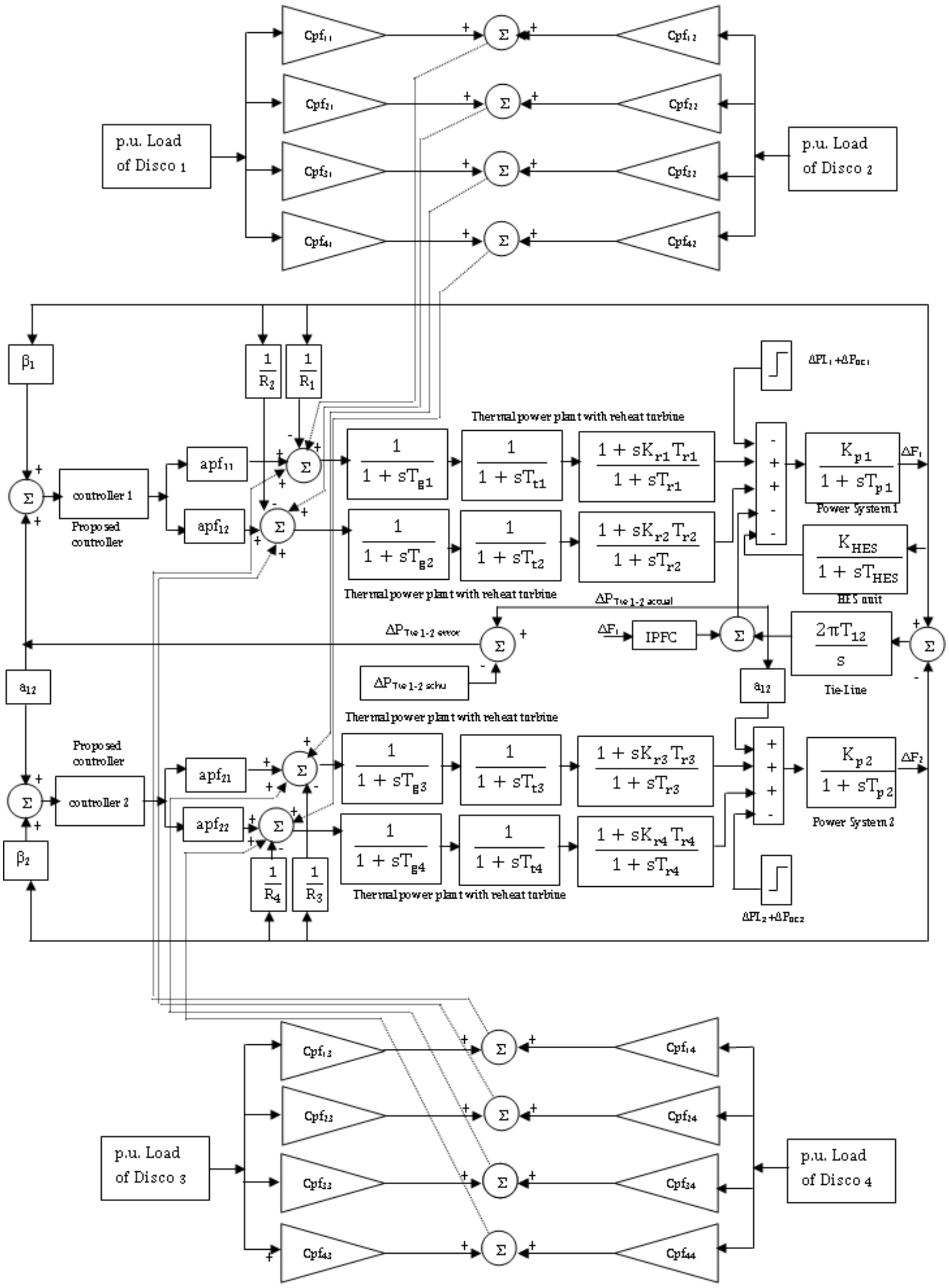

Fig. 5 Linearized model of a two-area Thermal reheat interconnected power system in a restructured environment with IPFC and HES devices.

IV. Over view of Krill Herd algorithm

Krill Herd (KH) algorithm is a class of nature-inspired algorithm which simulates the herding behavior of krill individuals. It has been successfully utilized to tackle many optimization problems in different domains and found to be very efficient. The most significant property of krill is that it can form large number of swarms. Whenever predators attack the krill swarms, density of krill and distance reaching to food location are reduced. The formation of krill is a multi-objective process which includes (i) increasing krill density and (ii) reaching food location quickly. The KHA is based on the simulation study of herding behaviour of krill individuals and was first developed by Gandomi and Alavi in 2011. Krill density and distance of krill individual from the food location are taken as an initialisation step of KHA. The location of a krill individual is affected by the following three factors: (i) Movement induced by other krill individuals; (ii) Foraging activity; and (iii) Random diffusion. So the location of the krill is expressed by the following Lagrangian model.

$$\frac{dx_i}{dt} = N_i + F_i + D_i \qquad (10)$$

where N_i , F_i and D_i are the motion induced by other krill's, foraging activity and physical diffusion of the ith krill individual respectively. The krill individuals always try to maintain a high density and move due to their mutual interaction with others. The movement of each krill individual is evaluated by the local, target and repulsive vector and may mathematically be expressed as follows.

$$N_i^{new} = N^{\max}\alpha_i + w_n \; N_i^{old} \tag{11}$$

where N^{max} is the maximum induced speed; α_i is the direction of motion which is approximately computed by the target effect, local effect and repulsive effect; w_n is the inertia weights of the motion induced and the range of [0, 1]; and N_i^{old} is the previous induced motion of the ith krill. Furthermore, α_i is defined as

$$\alpha_i = \alpha_i^{local} + \alpha_i^{t\arg et} \tag{12}$$

Where, α_i^{local} and α_i^{target} are the local effect provided by neighbours krill and target direction provided by the best krill individuals. The motion of a krill herd is influenced by two main effective factors: (i) the food location; and (ii) the previous experience about the food location. The expression of the motion can be stated as:

$$F_i = V_f \; \beta_i + \omega_f \; F_i^{old} \tag{13}$$

Where, V_f, ω_f and F_i^{old} are the forging speed, the inertia weight of the foraging motion, the last one, respectively. The physical diffusion of the krill individuals is a random process, and the motion associates with maximum diffusion speed and random directional vector. The equation of the physical diffusion can be defined by:

$$D_i = D_{\max} \; \delta \tag{14}$$

Where D_i *is* the maximum diffusion speed, δ is the random directional vector and its arrays are random values in [-1, 1]. The motion of krill swarm can be considered as a process toward the best fitness. So the position of a krill individual can be given by

$$x_i \; (t + \Delta t) = x_i(t) + \Delta t \; \frac{dx_i}{dt} \tag{15}$$

The parameter Δt is very important that can be treated as a scale factor of the speed vector. So it must be adjusted in terms of the optimization problem. The value of Δt is completely depends on the given search space. The basic representation of KHA is presented in Fig. 5.

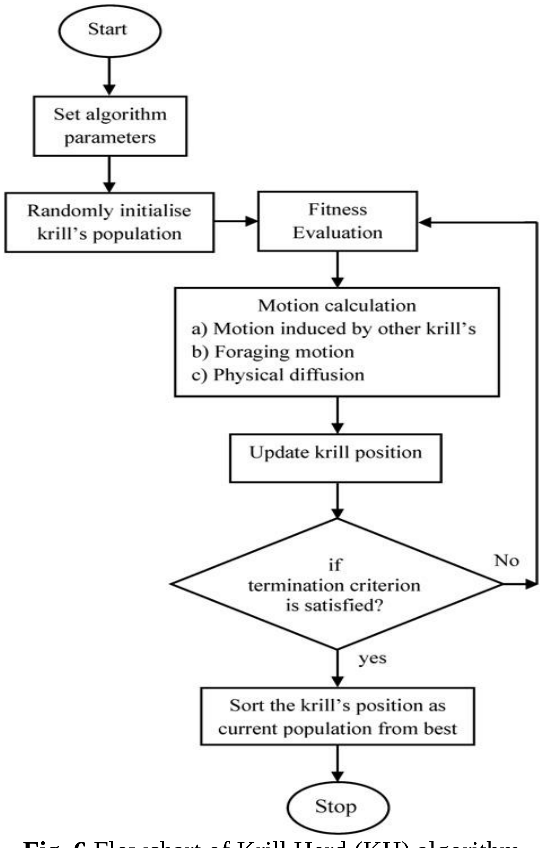

Fig. 6 Flowchart of Krill Herd (KH) algorithm

V. Evaluation Power System Restoration Indices

Power system restoration is well recognized as an important task to reduce the impact of a disturbance that occurs in power systems. The high level strategy of the System Restoration Plan is to restore the integrity of the interconnection as quickly as possible. The system restoration strategies are found closely related to the systems' characteristics. After analyzing the system conditions and characteristics of outages, system restoration planners or dispatchers will select the Power System Restoration (PSR) Indices which were obtained based on system dynamic performances and the remedial measures to be taken can be adjudged. In this study two-area thermal reheat interconnected power system without and with IPFC and HES units in a restructured environment are considered when the system is operating in a normal condition with all Gencos units in operation and are one or more Gencos unit outage in any area. The various Power System Restoration indices (PSR_1, PSR_2, PSR_3, PSR_4, PSR_5, PSR_6, PSR_7 and PSR_8) are calculated as follows

Step 1: The PSR_1 is obtained as the ratio between the settling time of frequency deviation in area 1 (ς_{s1}) and power system time constant (T_{p1}) of area 1

$$PSR_1 = \frac{\varsigma_{s1}}{T_{p1}} \tag{16}$$

Step 2: The PSR_2 is obtained as the ratio between the settling time of frequency deviation in area 2 (ς_{s2}) and power system time constant (T_{p2}) of area 2

$$PSR_2 = \frac{\varsigma_{s2}}{T_{p2}} \tag{17}$$

Step 3: The PSR_3 is obtained as the ratio between the settling time of Tie-line power deviation (ς_{s3}) and synchronous power coefficient T_{12}

$$PSR_3 = \frac{\varsigma_{s3}}{T_{12}} \tag{18}$$

Step 4: The PSR_4 is obtained as the peak value frequency deviation $\Delta F_1(\varsigma_p)$ response of area 1 exceeds the final value $\Delta F1(\varsigma_s)$

$$PSR_4 = \Delta F_1(\varsigma_p) - \Delta F_1(\varsigma_s) \tag{19}$$

Step 5: The PSR_5 is obtained as the peak value frequency deviation $\Delta F_2\ (\varsigma_p)$ response of area 2 exceeds the final value $\Delta F2(\varsigma_s)$

$$PSR_5 = \Delta F_2(\varsigma_p) - \Delta F_2(\varsigma_s) \tag{20}$$

Step 6: The PSR_6 is obtained as the peak value tie-line power deviation $\Delta P_{tie}\ (\varsigma_p)$ response exceeds the final value $\Delta P_{tie}\ (\varsigma_s)$

$$PSR_6 = \Delta P_{tie}(\varsigma_p) - \Delta P_{tie}(\varsigma_s) \tag{21}$$

Step 7: The PSR_7 is obtained from the peak value of the control input deviation $\Delta P_{c1}(\varsigma_p)$ response of area 1 with respect to the final value $\Delta P_{c1}(\varsigma_s)$

$$PSR_7 = \Delta P_{c1}(\varsigma_p) - \Delta P_{c1}\ (\varsigma_s) \tag{22}$$

Step 8: The PSR_8 is obtained from the peak value of the control input deviation $\Delta P_{c2}(\varsigma_p)$ response of area 2 with respect to the final value $\Delta P_{c2}(\varsigma_s)$

$$PSR_8 = \Delta P_{c2}(\varsigma_p) - \Delta P_{c2}\ (\varsigma_s) \tag{23}$$

VI. Simulation Results and Observations

The proposed controllers are designed and implemented in two-area thermal reheat interconnected restructured power system for different types of transactions. The test system consists of four Gencos each area consists of two Gencos for the thermal reheat unit with different capacity is shown in Fig 5. The nominal parameters are given in Appendix. The optimal solution of control inputs is taken an optimization problem, and the objective function in Eq (9) is derived using the frequency deviations of control areas and tie- line power changes. In bilateral based transactions, all Discos contracts with the Gencos for power as per the following DPM [6].

$$DPM = \begin{bmatrix} 0.5 & 0.25 & 0.5 & 0.4 \\ 0.2 & 0.25 & 0.2 & 0.2 \\ 0.0 & 0.3 & 0.2 & 0.25 \\ 0.3 & 0.2 & 0.1 & 0.15 \end{bmatrix} \quad (24)$$

In this case, the $Disco_1$, $Disco_2$, $Disco_3$ and $Disco_4$, demands 0.25 pu.MW, 0.05 pu.MW, 0.25 pu.MW and 0.05 pu.MW from Gencos as defined by cpf in the DPM matrix. Each Gencos for thermal-thermal system participates in AGC as defined by the following area participation factor $apf_{11} = apf_{12} = 0.5$ and $apf_{21} = apf_{22} = 0.5$. Apart from the normal operating condition of the test systems few other case studies like outage Genco-4 in area 2 and uncontracted power demand in any area and Disco Participation Matrix (24) is considered. The Proposed PI^+ and PIFI controller gains (K_{p1}, $K_{I1,}$ K_{p2}, K_{I2}) values of each area tuned simultaneously with help of KH algorithm for different type of transactions. The optimum controller parameter for various case studies is shown in Table 1 and 2. These proposed PI^+ and PIFI controllers are implemented in a test system and the simulation results shown in Fig 7. From the results, it can be observed that PIFI controller show better performance and convergence than that of the PI^+ controller. To make the system be stable and to improve the dynamic behaviour of same, coordinated control of IPFC and HES devices are incorporated with PIFI into the AGC loop. An alternative way to improve the performance of AGC is the initiation of HES devices facilities when the load demand is at its peak. Since HES can compensate active power variations with very little time delay. It can be used to enhance the AGC performance and boosts the reliability of power system during peak load. Besides these advantages, these storage facilities have also some supplementary dynamic benefits like load levelling, decrease in spinning reserve capacity, area regulation, long tie-line stabilization, black start capability and power factor correction in a power system. It can be observed that the oscillations in area frequencies and tie-line power deviations have decreased to a considerable extent as compared to that of the system without IPFC and HES devices 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 IPFC. Moreover, the tie-line power flow control by an IPFC units are found to be efficient and effective for Improving the dynamic performance of automatic generation control of inter connected power system. The various PSR indices are evaluated using Eq (16- 23) for PIFI controller based test system without and with IPFC and HES are tabulated in Tables 3 and 4 respectively.

6.1. Power System Restoration Assessment

The main focus in this paper is to obtain PSR indices which are useful for the system planners for adopting various restoration planning in advance.

(i) If $1.0 \leq PSR_1, PSR_2 \leq 5$ and $40 \leq PSR_3 \leq 50$, then the system subject to a large steady error for step load changes. The integral control action are required based on the performance criteria such as ACE must be equal to zero at least one time in all 10-minute periods and average deviation of ACE from zero must be within specified limits based on a percentage of system generation for all 10-minutes periods. So that the above case studies, the integral controller gain (K_I) is made very large then only steady state frequency error reduces to zero. In this case, PIFI controller gives better PSR indices as compared with PI^+ controller.

(ii) If $PSR_1, PSR_2 \geq 5$ and $PSR_3 \geq 50$ in this cases, the gain of the integrator is sufficiently high, over shoot will occur, increasing sharply as a function of the gain; this is highly undesirable. In the absence of integral control, one can sharply increase the gain of the closed- loop system and thereby improves the system response. However, the system will have a steady- state error. So that the FACTS devices coordinated with Energy Storage Systems (ESS) are used for AGC application has improve relatively stability of the power system and also to overcome the drawback of the designing integral controller.

(iii) If $0.5 \leq PSR_4, PSR_5 \leq 1$ and $0.15 \leq PSR_7, PSR_8, \leq 0.2$ In this case the conventional load-frequency controller may no longer be able to attenuate the large frequency oscillation due to the slow response of the governor for unpredictable load variations. Fast-acting energy storage systems having storage capacity in addition to the kinetic energy of the generator rotors is advisable to damp out the frequency oscillations. So that in deregulated system, regulation and load following are the two frequency-related ancillary services required for balancing the varying load with matching generation. Ancillary Services are defined as all those activities on the interconnected grid that are necessary to support the transmission of active power while maintaining reliable operation and ensuring the required degree of quality and security.

(iv) If $0.05 \leq PSR_6 \leq 0.15$ then the FACTS devices are needed to improvement tie-line power oscillations. As these FACTS devices are capable of controlling the network condition in a very fast manner the

usage of FACTS devices are more apt to improve the stability of power system. Several FACTS devices such as have been developed in recent decades. These FACTS devices are capable of controlling the network conditions in a very fast and economical manner.

(v) If PSR_4, PSR_5 ≥ 1, $PSR_6 \geq 0.15$ and PSR_7, $PSR_8 \geq 0.2$ then the system is vulnerable and the system becomes unstable and may result to blackout. Small blackouts, involving only a few substations, can often be handled rather easily since they occur more often than the larger blackouts so the operators has more experience with them and the load can often be reconnected as soon as the operational reserves are able to meet the demand. Larger blackouts, affecting the whole or significant parts of the power system, are much harder to restore since large parts of the power system need to be energized and a significant part of the generating units will not be available. In order to handle restoration situations the operators have prepared restoration plans and guidelines for some typical blackout situations. The operators have to adopt these to the current situation. Two major strategies in power system restoration can be defined, bottom up vs. top down. Bottom up means that several smaller electrical islands are started in parallel; these are then used to energize the transmission system. The need to synchronize the islands can slow down the process. Top down means that the transmission system is energized from one point and all the lower voltage levels are energized from the transmission system and the whole energized power system is kept synchronized.

(vi)

Table 1 Optimal PI^+ controller gain values using KH algorithm for two-area thermal reheat power system with corresponding Load demand change

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	0.392	0.543	0.236	0.227	0.15	0.15	0.0	0.0	0.0	0.0
Case 2	0.411	0.447	0.304	0.234	0.15	0.15	0.0	0.0	0.05	0.0
Case 3	0.474	0.508	0.342	0.248	0.15	0.15	0.0	0.0	0.0	0.05
Case 4	0.493	0.452	0.354	0.251	0.15	0.15	0.0	0.0	0.05	0.05
Case 5	0.437	0.493	0.361	0.253	0.25	0.05	0.25	0.05	0.0	0.0
Case 6	0.403	0.575	0.219	0.311	0.25	0.05	0.25	0.05	0.1	0.0
Case 7	0.436	0.591	0.221	0.328	0.25	0.05	0.25	0.05	0.0	0.1
Case 8	0.441	0.597	0.337	0.267	0.25	0.05	0.25	0.05	0.1	0.1
Case 9	0.457	0.585	0.353	0.343	0.08	0.22	0.08	0.22	0.0	0.0
Case 10	0.464	0.667	0.283	0.364	0.08	0.22	0.08	0.22	0.15	0.0
Case 11	0.484	0.631	0.374	0.286	0.08	0.22	0.08	0.22	0.0	0.15
Case 12	0.501	0.688	0.366	0.323	0.08	0.22	0.08	0.22	0.15	0.15

Table 2 Optimal PIFI controller gain values using KH algorithm for two-area thermal reheat power system with corresponding Load demand change

Test system	PIFI controller gain values in area1		PIFI controller gain values in area2		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	0.372	0.692	0.212	0.351	0.15	0.15	0.0	0.0	0.0	0.0
Case 2	0.384	0.572	0.284	0.353	0.15	0.15	0.0	0.0	0.05	0.0
Case 3	0.441	0.634	0.302	0.364	0.15	0.15	0.0	0.0	0.0	0.05
Case 4	0.484	0.578	0.341	0.378	0.15	0.15	0.0	0.0	0.05	0.05
Case 5	0.415	0.618	0.345	0.372	0.25	0.05	0.25	0.05	0.0	0.0
Case 6	0.373	0.688	0.204	0.428	0.25	0.05	0.25	0.05	0.1	0.0
Case 7	0.405	0.652	0.211	0.437	0.25	0.05	0.25	0.05	0.0	0.1
Case 8	0.412	0.675	0.322	0.478	0.25	0.05	0.25	0.05	0.1	0.1
Case 9	0.427	0.682	0.341	0.466	0.08	0.22	0.08	0.22	0.0	0.0
Case 10	0.443	0.712	0.275	0.484	0.08	0.22	0.08	0.22	0.15	0.0
Case 11	0.468	0.736	0.360	0.499	0.08	0.22	0.08	0.22	0.0	0.15
Case 12	0.476	0.778	0.352	0.448	0.08	0.22	0.08	0.22	0.15	0.15

Table 3 PSR Indices for Optimized PIFI based two-area thermal reheat power system

Test system	PSR indices based on Settling time (ς_s)			FRI based on Peak over/ under shoot (M_p)			FRI based on control input deviation (ΔP_c)	
	PSR_1	PSR_2	PSR_3	PSR_4	PSR_5	PSR_6	PSR_7	PSR_8
Case 1	0.818	0.815	28.14	0.324	0.283	0.028	0.121	0.088
Case 2	0.853	0.817	29.62	0.542	0.374	0.039	0.207	0.099

Case 3	0.821	0.872	32.27	0.407	0.423	0.045	0.121	0.224
Case 4	1.138	1.292	36.38	0.593	0.698	0.062	0.204	0.210
Case 5	0.837	0.837	26.27	0.257	0.339	0.053	0.096	0.047
Case 6	0.884	0.849	27.26	0.472	0.404	0.054	0.214	0.102
Case 7	0.881	0.925	30.47	0.306	0.569	0.061	0.114	0.111
Case 8	1.175	1.238	38.33	0.562	0.907	0.062	0.208	0.124
Case 9	1.192	1.368	49.84	0.411	0.411	0.108	0.164	0.145
Case 10	1.507	1.434	49.68	0.468	0.523	0.132	0.175	0.157
Case 11	1.517	1.732	57.38	0.572	0.838	0.149	0.187	0.173
Case 12	1.714	1.768	57.95	1.185	1.120	0.165	0.218	0.185

Table 4 PSR Indices for Optimized PIFI based two-area thermal reheat power system with IPFC and HES unit

Test system	PSR indices based on Settling time (ς_s)			FRI based on Peak over/ under shoot (M_p)			FRI based on control input deviation (ΔP_c)	
	PSR_1	PSR_2	PSR_3	PSR_4	PSR_5	PSR_6	PSR_7	PSR_8
Case 1	0.702	0.692	22.02	0.222	0.178	0.021	0.102	0.057
Case 2	0.731	0.701	23.47	0.331	0.271	0.032	0.194	0.064
Case 3	0.695	0.756	26.11	0.202	0.318	0.037	0.108	0.201
Case 4	1.023	1.177	32.15	0.379	0.594	0.054	0.184	0.187
Case 5	0.714	0.714	20.04	0.151	0.238	0.045	0.081	0.015
Case 6	0.761	0.739	21.21	0.268	0.297	0.046	0.201	0.064
Case 7	0.754	0.812	24.33	0.101	0.465	0.051	0.102	0.084
Case 8	1.051	1.114	31.37	0.357	0.796	0.052	0.198	0.091
Case 9	1.071	1.241	41.55	0.206	0.307	0.101	0.147	0.107
Case 10	1.014	1.314	42.01	0.263	0.419	0.121	0.162	0.127
Case 11	1.093	1.503	45.35	0.412	0.618	0.129	0.155	0.124
Case 12	1.294	1.593	46.04	0.645	0.812	0.138	0.173	0.138

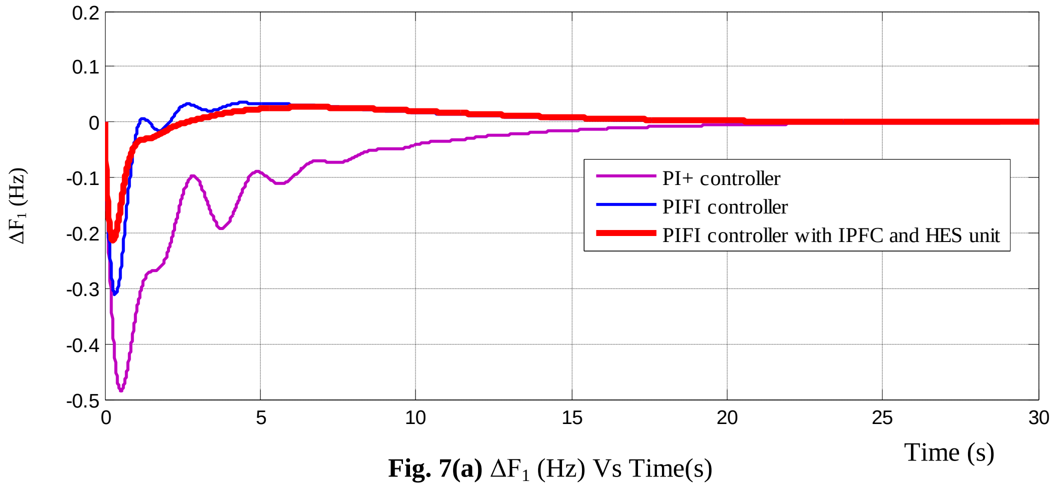

Fig. 7(a) ΔF_1 (Hz) Vs Time(s)

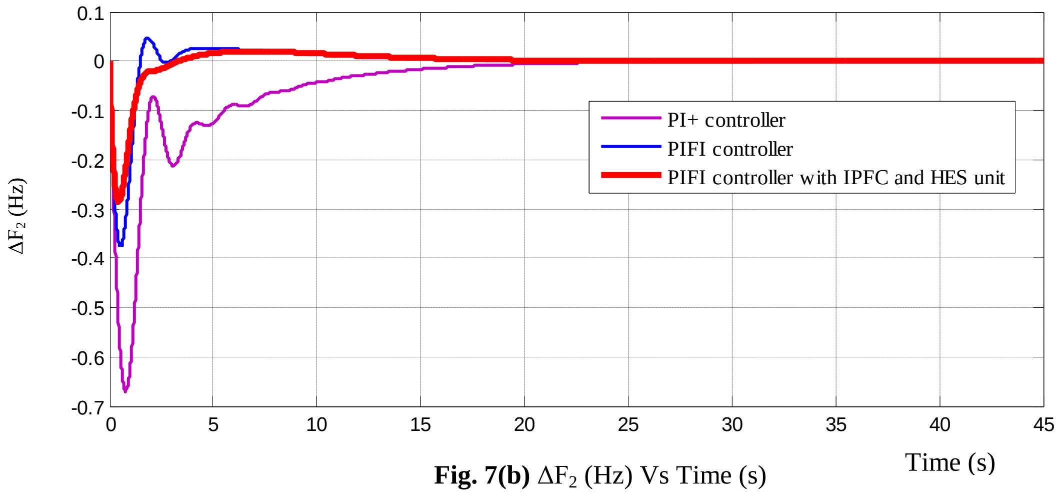

Fig. 7(b) ΔF_2 (Hz) Vs Time (s)

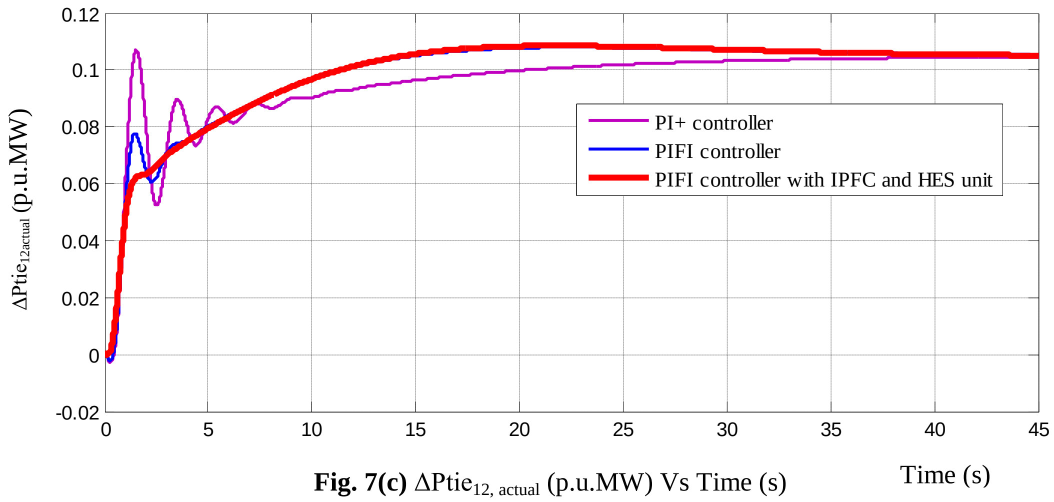

Fig. 7(c) $\Delta Ptie_{12,\ actual}$ (p.u.MW) Vs Time (s)

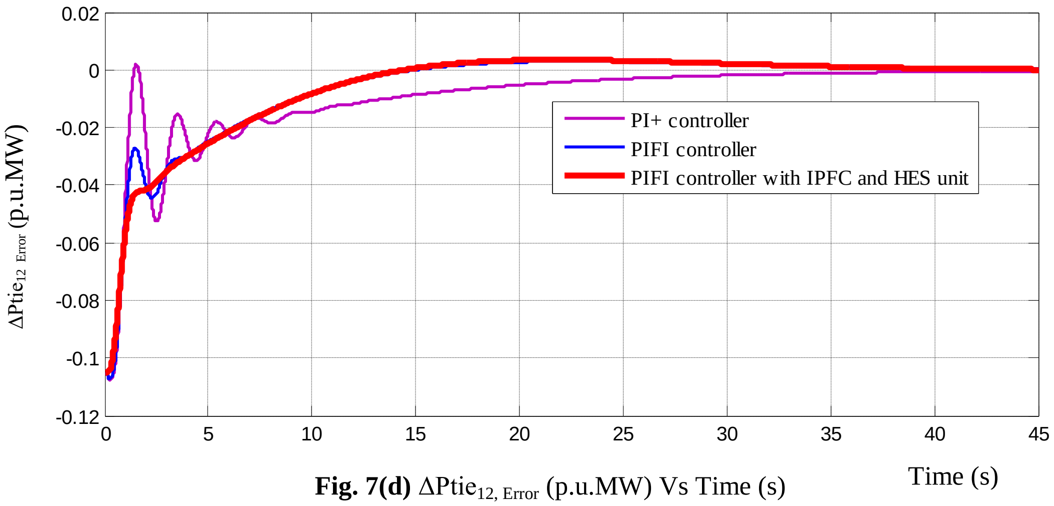

Fig. 7(d) $\Delta Ptie_{12,\ Error}$ (p.u.MW) Vs Time (s)

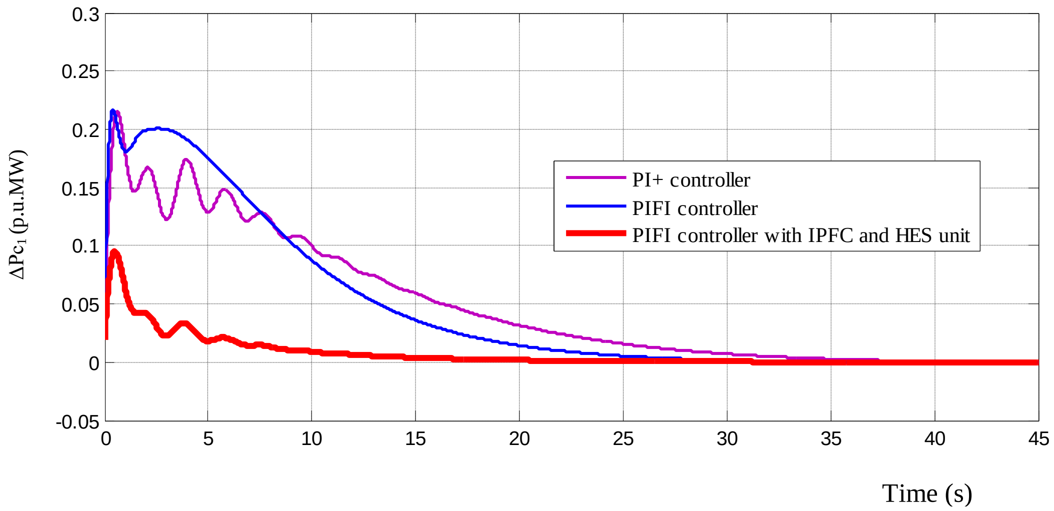

Fig. 7(e) ΔPc_1 (p.u.MW) Vs Time (s)

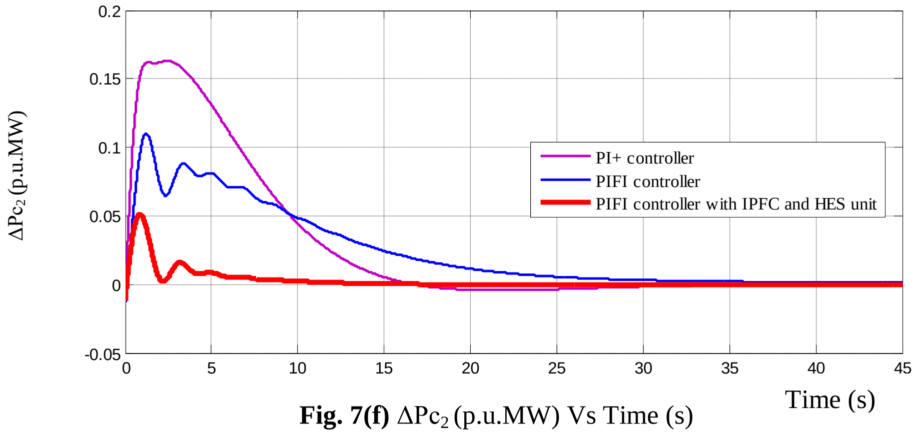

Fig. 7(f) ΔPc_2 (p.u.MW) Vs Time (s)

Fig.3 Dynamic responses of the frequency deviations, tie- line power deviations, and Control input deviations for a two area thermal reheat power system without and with IPFC and HES using PI^+ controllers (case-5)

VII. Conclusion

The PI^+ and PIFI controllers are designed using KH algorithm and implemented in a two area thermal reheat interconnected power system for different types of transactions. The dynamic output response of test system is found to have much improvement in the frequency deviations of each area, tie-line power oscillations with the use of the PSR indices and with the adoption of PIFI controller when compared with that of PI^+ controller. The proposed PIFI controller produces a phase lead in a certain frequency range without having a derivative term, enhancing the control performances and stability robustness. The simulation results demonstrate that KH algorithm is able to reach the optimal solution irrespective of the large variation with a faster convergence rate. From the simulated results it is observed that the PSR indices calculated for a test system without / with FACTS devices using PI^+ controller indicates that more sophisticated control action is required for a better restoration of the power system output responses and to ensure improved PSR indices in order to provide good margin of stability. Moreover, the tie-line power flow control by an IPFC units are found to be efficient and effective for Improving the dynamic performance of load frequency control of inter connected power system. A HES unit contributes a lot in promoting the efficiency of the overall generation control through the effect of the use in load leveling and the assurance of AGC capacity after overload characteristic and quick responsiveness. It may be concluded that, PSR indices have improved by the HES and IPFC unit in order to sufficient margin of AGC capacity absorbs the speed governor capability in excess of falling short of the frequency bias value and tie-line power flow control by an IPFC.

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APPENDIX – A

A1. Control Area parameter [22]

Parameters	Area 1	Area 2
k_p (Hz/p.u.MW)	120	72
T_p (sec)	20	14.3
β (p.u.MW / Hz)	0.8675	0.785
T_{ij} (p.u.MW / Hz)	$T_{12} = 0.545$	
F (Hz)	60	
a_{12}	-1	

A2 Gencos Parameter (Thermal generating unit) [22]

MVA_{Base} (1000 MW) Parameters	Gencos (k in area i)			
	1-1	1-2	2-1	2-2
Rate (MW)	1000	1100	800	900
T_g (sec)	0.06	0.06	0.07	0.08
T_t (sec)	0.36	0.44	0.42	0.4
T_r (sec)	10	10	10	10
K_r	0.5	0.5	0.5	0.5
R (Hz / p.u.MW)	2.4	2.5	3.3	2.4
apf	0.5	0.5	0.5	0.5

A3 Data for FACTS devices [18, 20]

Devices	Parameters Value
IPFC	T_{IPFC} = 0.01s, T_w = 10s, T_1 =0.235s, T_2=0.712s, T_3 =0.895s, T_4=0.105s, k_1=0.43 and k_2=0.53
HES	K_{HES} = 0.02, K_{FC}=0.01, T_{HES}=0.5s,T_{FC}= 4s

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