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Control Performance Standard based Load Frequency Controller for a Two - Area Interconnected Thermal Reheat Power System coordinated with TCPS and SCES units

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Abstract - This paper proposes a design of Bacterial Foraging Optimization (BFO) based Proportional plus Integral Controller using Control Performance Standard (CPS) Criterion for the load - frequency control of a two - area interconnected thermal reheat power system without and with Super Capacitor Energy Storage (SCES) units considering Thyristor Controlled Phase Shifter (TCPS) in series with the Tie-line. TCPS ensures the stabilization of the area frequency oscillations of the inter - area mode in the interconnected power system by the dynamic power flow control in the tie-line. The Control Performance Standard (CPS) criterion is adopted to the fuzzy controller design and the BFO technique is used to optimize the PI gain setting by minimize a quadratic performance index (cost function) to improve the dynamic quality of the system. The system was simulated and the output responses of the frequency deviations in area 1, area 2, tie-line power deviations and control input deviations for 1% step load disturbance in area 1 were obtained. The result reveals that the SCES coordinated with TCPS units has greater potential for improving the system dynamic performance than that of the system without SCES unit and TCPS unit.

Keywords: **Load Frequency Control, Bacterial Foraging Optimization, Area Requirement Criterion, Control Performance Standard, Super Capacitor Energy Storage, Thyristor Controlled Phase Shifter.**

I. INTRODUCTION

The reliability and quality of the power generation and distribution in an interconnected power system mainly depends on satisfying the system frequency and terminal voltages within the specified limit. The difference between generated power and instant load demand causes change in nominal system frequency at a normal state. If the amount of generated power is less than the demanded amount, the speed of the generator units and the frequency of the power generation begin to decrease and vice versa. Hence, the amount of power produced by each generator should take care in minimizing the frequency deviations occurred in the power system due to sudden change in load demand. For this purpose, the load frequency control is being used and the main aim of this control is to ensure zero steady state error of the system frequency deviations following a step load demand in a faster manner. The stabilization of frequency oscillations in an interconnected power system becomes challenging when implemented in the future environment due to the large load demand even though quality of power generation is ensured. So advance economic, high efficiency and improved control schemes [1-3] are required to ensure the power system reliability.

One of the fascinating important Distribution Generation (DG) that can be enhanced for the power quality improvement is the Gas Turbines. Gas Turbine (GT) units with a maximum capacity can be applied not only as a fast energy compensation device for large loads but also to damp out the frequency and tie-line deviations, which makes it a cost-effective system [4-6]. Moreover GT becomes increasingly popular in different power scenario due to their green-house emission as well as higher efficiency especially when connected in a Combined Cycle Power Plant [6].

The influence of the power generation and the absorption of the power fluctuations have to be effectively be controlled for the better quality of the power system and this can be imposed by incorporating Super Capacitor Energy Storage (SCES) unit. The problems like low discharge rate, increased time required for power flow reversal and maintenance requirements have led to the evolution of Super Capacitor Energy Storage (SCES) or Ultra Capacitor Energy Storage (UCES) devices for their applications also load frequency stabilizers. Super capacitors are used to store electrical energy during surplus generation and deliver high power within a short duration of time especially during the peak-load demand period [7-9]. The SCES will, in addition to load leveling, a function conventionally assigned to them, have a wide range of applications for power quality improvement, standby by for the decentralized power sources under maintenance. The SCES are excellent for short-time overload compensation and the response characteristics possessed by them are of high quality in particular.

In recent years, the fast progress in the field of power electronics had opened new opportunities in designing various FACTS devices and utilization of the devices in most effective way is to improve the power system operation and to regulate the power transfer limits. A Thyristor Controlled Phase shifter (TCPS) is regarded as one of the versatile devices in the FACTS device family which is expected to bean effective apparatus for the tie-line power flow control of an interconnected power system [10-12]. It injects a variable series voltage to the tie - line to ensure a better power transfer capability by modifying the phase angle [11]. The TCPS is found to be superior than that of governor system because of its high - speed performance. When a sudden load perturbation occurs in the interconnected power system TCPS quickly starts the control to suppress the peak value of the transient frequency deviation. Thus, the TCPS is essentially as equipment to modulate active power flow in power system and its fast active operation make the TCPS attractive to use for the improvement system operation and control.

Nowadays the power system complexities are being solved using Evolutionary Computation methods (EC) such as Differential Evolution (DE) [13], Genetic Algorithms (GAs) [14], Particle Swarm Optimizations (PSO) [15], Ant Colony Optimization (ACO) [16], Artificial Bee Colony Optimization (ABCO) [17] which are some of the heuristic techniques having the capability of determining global optimum. Classical approach based optimization for controller gains is a trial and error method and extremely time consuming when several parameters have to be optimized simultaneously and provides suboptimal result. Some authors have applied genetic algorithm (GA) to optimize the controller gains more effectively and efficiently than the classical approach. But recent research has brought out some deficiencies in GA performance [15]. The premature convergence of GA degrades its search capability. The Bacterial Foraging Optimization (BFO) mimics how bacteria forage over a landscape of nutrients to perform parallel non-gradient optimization [18]. The BFO algorithm is a computational intelligence based technique that is not widely affected by the size and nonlinearity of the problem and can be able to arrive the convergence to the optimal solution in many problems where most analytical methods fail to convergence. A more recent and powerful evolutionary computational technique BFO [19] is found to be user friendly and is adopted for simultaneous optimization of several parameters for both primary and secondary control loops of the governor.

Control Performance Criteria (CPC) has been formerly used to evaluate LFC performance. The Control Performance Standard (CPS) is specifically designed to comply with the performance standards imposed by the North American Electric Reliability Council (NERC) for equitable operation of an interconnected system. Control Performance Standard (CSP1) and Control Performance Standard 2 (CPS2) are derived from rigorous theoretical basis [20-22]. CPS1 is a measurement to assess the performance of frequency control in each area. CPS2 is designed to restrain the ACE 10-min average value and in doing so provides a means to limit excessive unscheduled power flows that could results from large ACE [22]. Considering the power system load frequency control, this paper establishes a fuzzy logic controller to predict the future frequency of the target object, thus forecasting the optimized controller's design, which follows the CPS performance standards through the fuzzy logic rules. This paper adopts CPS1 and CPS2 as input to the fuzzy logic controller and output gain of fuzzy controller adjust the control parameter gain depending up on the NERC's compliance.

II. PROBLEM FORMULATION

The state space representation of the minimum realization model of N area interconnected power system may be expressed as [3].

$$\dot{x} = Ax + Bu + \Gamma d \qquad (1)$$

$$y = Cx \qquad (2)$$

where $x = [x_1^T, \Delta p_{ei} .. x_{(N-1)}^T, \Delta p_{e(N-1)} .. x_N^T]^T \qquad (3)$

n - State vector $\qquad n = \sum_{i=1}^{N} n_i + (N-1)$

$u = [u_1,...u_N]^T = [\Delta P_{C1}...P_{CN}]^T$ N-Control Input vector

$d = [d_1,...d_N]^T = [\Delta P_{D1}....P_{DN}]^T$ N-Disturbance Input vector

$y = [y_1....y_N]^T$ 2N- Measurable output vector

where A is system matrix, B is the input distribution matrix, Γ is the disturbance distribution matrix, C is the control output distribution matrix, x is the state vector, u is the control vector and d is the disturbance vector representing change in load.

III. MODELING OF A GAS TURBINE UNIT

A Gas Turbine unit transfer function model is shown in figure 1 which is one of the most commonly used dynamic models and has also been used in this methodology. Gas Turbines have the advantages like Quick start-up/shut-down, low weight and size, cost of installation is less, low capital cost, black start capability, high efficiency requires less cranking power, pollutant emission control etc. When the load is suddenly increased the speed drops quickly but the regulator reacts and increases the fuel flow to a maximum of 100%, thereby improving the efficiency of the system [4]. Amid growing concerns about green-house emissions, gas turbines have been touted as a viable option, due to their higher efficiency and the lower green-house emissions compared to other energy sources and fast starting capability which enables them to be used even as peaking units that respond to peak demands.

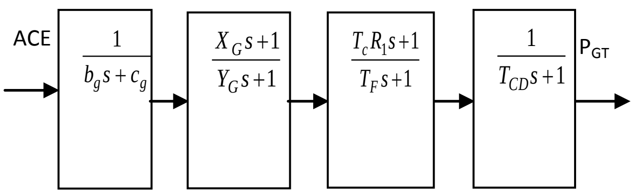

Fig. 1. Transfer Function representation of a Gas Turbine unit

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IV. MODELING OF A SUPER CAPACITOR ENERGY STORAGE UNITS

The block diagram representation of the Super Capacitor Energy Storage (SCES) is shown in fig 2.

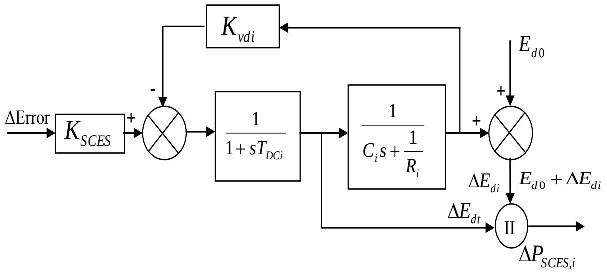

Fig.2. Block diagram with capacitor voltage deviation feedback.

Either frequency deviation or Area Requirement (AR) can be used as the control signal to the SCES unit ($\Delta_{errori} = \Delta F_i$ or AR_i). E_{di} is then continuously controlled in accordance with this control signal. For the i[th] area, if the frequency deviation ΔF_i (i.e.,$\Delta_{errori} = \Delta F_i$) of the power system is used as the control signal to SCES, then the deviation in the current, ΔI_{di} is given by

$$\Delta I_{di} = \left[\frac{1}{1+sT_{DCi}}\right][K_{SCES,\,i}\cdot\Delta F_i - K_{vdi}\cdot\Delta E_{di}] \quad (4)$$

If the tie-line power flow deviations can be sensed, then the Area Requirement (AR) can be fed to the SCES as the control signal (i.e., $\Delta_{errori} = \Delta R_i$). Being a function of tie-line power deviations, AR as the control signal to SCES, may further improve the tie-power oscillations. Thus, if AR_i is the control signal to the SCES, then the deviation in the current ΔI_{di} would be

$$\Delta I_{di} = \left[\frac{1}{1+sT_{DCi}}\right][K_{SCES,i}\cdot\Delta\Delta A_i - K_{vdi}\cdot\Delta E_{di}];\ i,j=1,2 \quad (5)$$

The control actions of Super Capacitor Energy Storage units are found to be superior to the action of the governor system in terms of the response speed against, the frequency fluctuations.

V. TIE – LINE POWER FLOW MODEL CONSIDERING TCPS

The figures 3 shows the schematic diagram of a two – area interconnected reheat thermal power system with TCPS in series with tie line the TCPS is placed near area 1. Although, there are a variety of TCPS configurations, the basic characteristics for the power flow control are the same. Thus, the mathematical model of a TCPS for stabilization of frequency oscillations is derived from the power flow control characteristics of the TCPS.

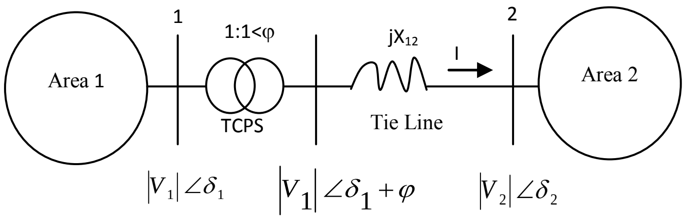

Fig 3. A schematic of two-area reheat thermal power system with TCPS in Series with tie-line

In the figure 3, the current I can be expressed as

$$I_{12} = \frac{|V_1|\angle(\delta_1+\varphi) - |V_2|\angle(\delta_2)}{jX_{12}} \quad (6)$$

From Fig. 3

$$P_{tie12} - jQ_{tie12} = V_1^* I_{12} |V_1|\angle-(\delta_1+\varphi)\frac{|V_1|\angle(\delta_1+\varphi) - |V_2|\angle(\delta_2)}{jX_{12}} \quad (7)$$

Separating the real parts of eqn (7),

$$P_{tie12} = \frac{|V_1||V_2|}{X_{12}}\sin(\delta_1-\delta_2+\varphi) \quad (8)$$

In (8), perturbing δ_1, δ_2 and φ from their nominal values δ^0_1, δ^0_2 and φ^0 yields:

$$\Delta P_{tie1,2} = \frac{|V_1||V_2|}{X_{12}}\cos(\delta_1^0-\delta_1^0+\varphi^0)\sin(\Delta\delta_1-\Delta\delta_2+\Delta\varphi) \quad (9)$$

$(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi)$ is very small since, for a small change in real power load, the variation of bus voltage angles as well as the variation of TCPS phase angle are practically very small.

Hence, $\sin(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi) \approx (\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi)$

Therefore,

$$\Delta P_{tie1,2} = \frac{|V_1||V_2|}{X_{12}}\cos(\delta_1^0-\delta_2^0+\varphi^0)(\Delta\delta_1-\Delta\delta_2+\Delta\varphi) \quad (10)$$

$$T_{12} = \frac{|V_1||V_2|}{X_{12}}\cos(\delta_1^0-\delta_2^0+\varphi^0) \quad (11)$$

Thus, eqn (10) reduces to

$$\Delta P_{tie1,2} = T_{12}(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi) \quad (12)$$

$$\therefore \Delta P_{tie1,2} = T_{12}(\Delta\delta_1 - \Delta\delta_2) + T_{12}\Delta\varphi \quad (13)$$

As $\Delta\delta_1 = \int\Delta\omega_1\,dt$ and $\Delta\delta_2 = \int\Delta\omega_2\,dt \quad (14)$

From eqn (13) and eqn (14),

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$$\Delta P_{tie1,2} = T_{12} \left(\int \Delta\omega_1 \, dt - \int \Delta\omega_2 \, dt\right) + T_{12} \, \Delta\varphi \, (s) \quad (15)$$

Taking Laplace transformation for eqn (15) yields

$$\Delta P_{tie12}(s) = \frac{T_{12}}{s} [\Delta\omega_1(s) - \Delta\omega_2(s)] + T_{12} \, \Delta\varphi(s) \quad (16)$$

As per (16), tie-line power flow can be controlled by controlling the phase shifter angle $\Delta\varphi$.

The phase shifter angle $\Delta\varphi$ (s) can be represented as:

$$\Delta\varphi(s) = \frac{K\varphi}{1 + sT_{PS}} \Delta Error(s) \quad (17)$$

Therefore, (17) can be rewritten as

$$\Delta P_{tie1,2}(s) = \frac{T_{12}}{s} [\Delta\omega_1(s)] + T_{12} \frac{K\varphi}{1 + sT_{PS}} \Delta Error(s) \quad (18)$$

If the speed deviation $\Delta\omega_1$ is sensed, it can be used as the control signal (i.e.ΔError = $\Delta\varphi_1$) to the TCPS unit to control the TCPS phase shifter angle which in turn, controls the tie-line power flow. Thus,

$$\Delta\varphi(s) = \frac{K\varphi}{1 + sT_{PS}} \Delta\omega_1(s) \quad (19)$$

And the tie-line power flow perturbation becomes

$$\Delta P_{tie1,2}(s) = \frac{T_{12}}{S} [\Delta\omega_1(s) - \Delta\omega_2(s)] + T_{12} \frac{K\varphi}{1 + sT_{PS}} \Delta\omega_1(s) \quad (20)$$

$$\Delta P_{tie1,2}(s) = \Delta P^0_{tie12}(s) + \Delta P_{TCPS}(s)$$

When $\Delta P_{TCPS}(s) = T_{12} \frac{K\varphi}{1 + sT_{PS}} \Delta\omega_1(s)$

The structure of TCPS as a frequency controller is shown in Fig.4. The per unit rotor deviation ($\Delta\omega_i$, i=1,2) which provides the information of each mode of interests is used as the input signal for the controller. K_f is the gain block having the value equal to nominal system frequency. There are two parameters such as stabilization gain $K\varphi$ and time constant T_{PS} to be optimized for the optimal design of the TCPS frequency controller.

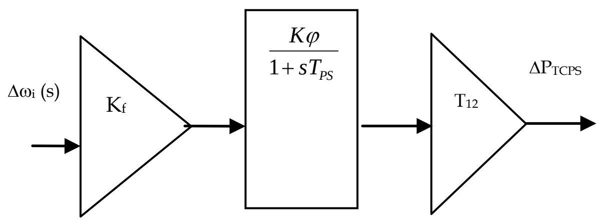

Fig 4. Structure of TCPS as a frequency Controller

VI. DESIGN OF PI CONTROLLER USING BACTERIAL FORAGING OPTIMIZATION (BFO) TECHNIQUE

BFO method was invented by Kevin M. Passion [19] motivated by the natural selection which tends to eliminates the animals with poor foraging strategies and favor those having successful foraging strategies. The foraging strategy is governed by four processes namely chemotaxis, swarming, reproduction and elimination and dispersal.

(i) Chemotaxis:

Chemotaxis process is the characteristics of movement of bacteria in search of food and consists of two processes namely swimming and tumbling. A bacterium is said to be swimming if it moves in a predefined direction, and tumbling if it starts moving in an altogether different direction. Let, j be the index of chemotactic step, k be reproduction step and *l*' be the elimination dispersal event. $\theta_i(j,k,l)$ is the position of i^{th} bacteria at j^{th} chemototactic step k^{th} reproduction step and l^{th} elimination.

$$\theta^i(j+1, k, l) = \theta^i(j, k, l) + C(i) \frac{\Delta(i)}{\sqrt{\Delta^T(i) \, \Delta(i)}} \quad (21)$$

Where C (i) denotes step size

Δ (i) Random vector

Δ^T (i) Transpose of vector Δ(i)

If the health of the bacteria improves after the tumble, the bacteria will continue to swim to the same direction for specified steps (or) until the health degrades

(ii) Swarming:

Bacteria exhibits swarm behavior ie. Healthy bacteria try to attract other bacterium so that they reach the desired location (solution point) together more rapidly. The effect of swarming is to make the bacteria congregate into groups and moves as concentric patterns with high bacterial density mathematically swarming behavior can be model as

$$J_{CC}(\theta, p(j, k, l)) = \sum_{i=1}^{S} J^i cc\,(\theta, \theta_i(j, k, l))$$

$$= \sum_{i=1}^{S} \left[-d_{attract} \exp\left(-\omega_{attract}\right) \sum_{m=1}^{p} \left(\theta^m - \theta^i_m\right)^2 \right] + \sum_{i=1}^{s} \left[-d_{repelent} \exp\left(-\omega_{repelent}\right) \sum_{m=1}^{p} \left(\theta^m - \theta^i_m\right)^2 \right] \quad (22)$$

Where

J_{CC} - Relative distance of each bacterium from the fittest bacterium

S - Number of bacteria

p - Number of parameters to be optimized

θ^m-Position of the fittest bacteria

$d_{attract}$, $\omega_{attract}$, $d_{repelent}$, $\omega_{repelent}$ - parameters

(iii) Reproduction:

In this step, population members who have had sufficient nutrients will reproduce and the least healthy bacteria will die. The healthier population replaces unhealthy bacteria which gets eliminated wing to their poorer foraging

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Volume 3, Issue 3, September 2013

abilities. This makes the population of bacteria constant in the evolution process.

(iv) Elimination and dispersal:

In the evolution process a sudden unforeseen event may drastically alter the evolution and may cause the elimination and or dispersion to a new environment. Elimination and dispersal helps in reducing the behavior of stagnation i.e, being trapped in a premature solution point or local optima.

Steps involved in Bacterial Foraging Optimization Algorithm

In case of BFO technique each bacterium is assigned with a set of variable to be optimized and are assigned with random values [Δ] within the universe of discourse defined through upper and lower limit between which the optimum value is likely to fall. In the proposed method the proportional (KPi) plus Integral gains (KIi) during scheduling, each bacterium is allowed to take all possible values within the range and the cost objective function [J] which is represented by eqn (31) is minimized. In this study, the BFO algorithm reported in [18] is found to have better convergence characteristics and is implemented as follows.

Step 1- Initialization

The following parameters are initialized.

a. Number of parameter (p) to be optimized. In this study K_{P1}, K_{P2}, K_{I1} and K_{I2}.
b. Number of bacteria (S) to be used for searching the total region.
c. Swimming length (Ns), after which tumbling of bacteria will be undertaken in the chemotactic loop.
d. The number of iteration to be undertaken in a chemo tactic loop N_C; (N_C>N_S).
e. The maximum number of reproduction N_{re} to be undertaken.
f. The maximum number of elimination (N_{ed}) and dispersal events to be imposed over bacteria.
g. p_{ed} be the probability with which the elimination and dispersal will continue.
h. The location of each bacterium P (1-p,1-s,1) which is specified by random numbers within [-1,1].
i. The value of C (i) which is assumed to be constant for all bacteria to simplify the design strategy.
j. The values of $d_{attract}$, $W_{attract}$, $d_{repelent}$ and $W_{repelent}$ are shown in Table 1. It is to be noted here that the value of $d_{attract}$ and $d_{repelent}$ must be same so that the penalty imposed on the cost function through "J_{CC}" of (22) will be "0" when all the bacteria will have same value, i.e., they have converged.
k. After initialization of all the above variables, keeping one variable changing and others fixed with value of the proposed "J".

Table 1: BFO Parameters

Sl. No	Parameters	Value
1	Number of Bacterium (s)	10
2	Swimming length (N_s)	3
3	Number of iteration in a Chemotactic loop (N_c)	10
4	Number of reproduction (N_{re})	15
5	Number of elimination and dispersal event (N_{ed})	2
6	Probability with which the elimination and dispersal(P_{ed})	0.25
7	Number of Parameters(P)	4
8	$W_{attract}$	0.04
9	$d_{attract}$	0.01
10	$d_{repellent}$	0.01
11	$W_{repelent}$	10

Step - 2 Iterative algorithms for optimization

This section models the bacterial population chemotaxis is swarming, reproduction, elimination, and dispersal (initially j=k=l=0) for the algorithm updating θ^i automatically results in updating of 'P'.

(1) Elimination –dispersal loop: $l=l+1$

(2) Reproduction loop: k=k+1

(3) Chemotaxis loop: j=j+1

(a) For i=1,2,…..S, calculate cost for each bacterium i as follows.

- Compute value of cost J (i, j, k, j), Let $j_{sw}(i,j,k,l) = J(i,j,k,l) + J_{cc}(\theta^i(j,k,l), P(j,k,l))$ (23) [ie, add on the cell to cell attractant effect obtain through (26) for swarming behavior to the cost value obtained through (31)].
- Let J_{last}=J_{sw} (i, j, k,l) save this value since we may find a better cost via a run
- End of the loop.

(b) for i=1,2….S take the tumbling / swimming decision

- Tumble: generate a random vector
  Δ (i) $\in \Re^p$ with each element,
  Δ_m (i) m= 1,2,………p, a random number on [-1,1].
- Move let

$$\theta^i(j+1,k,l) = \theta^i(j,\ k,\ l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \qquad (24)$$

  Fixed step size in the direction of tumble for bacterium 'i' is considered
- Compute and then let J (i, j+1,k,) and then let

$$J_{SW}(i,j+1,k,l) = J(i,j+1,k,l) + J_{CC}(\theta^i(j+1,k,l)P(j+1,k,l)) \qquad (25)$$

Swim:

(i) Let m=0;(counter for swim length)

(ii) While m<Ns (have not climbed down too long)

- Let m=m+1

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Volume 3, Issue 3, September 2013

If J_{sw} (i,j+1,k,*l*) <J_{last} (if doing better), let

$J_{last} = J_{sw}$ (i,j+1, k,*l*) and in eqn.(26)

And use this θ^i (j+1,k,*l*) to compute the new J(i, j+1, k,*l*).

Else let m=N_s. This the end of while statement

(c) Next bacterium (i+1) is selected if i ≠S (ie go to b) to process the next bacterium

4) If j<N_c go to step 3. In this case, chemotaxis is continued since the life of the bacteria in not over

5) Reproduction.

a) for the given k and *l* for each i=1,2………S let

$$J^i_{health} = \min_{j\in\{1....Ne\}} [J_{sw}(i,j,k,l)] \quad (26)$$

be the health of the bacterium i (a measure of how many nutrients it) got over its life time and how successful if it was at avoiding noxious substance. Sort the bacteria in the ascending order based on the cost J_{health} (higher cost means lower health).

b) The Sr =S/2 bacteria with highest J_{health} values die and other Sr bacteria with the best value split and the copies that are placed at the same location as their parent.

6) if k<N_{re}, go to 2; in this case, as the number of specified reproduction steps have not been reached, so the next generation in the chemotactic loop is to be started.

7) Elimination –dispersal: for i = 1,2… S with probability N_{ed}, eliminates and disperses each bacterium [this keeps the number of bacteria in the population constant] to a random location on the optimization domain.

VII. AREA REQUIREMENT (AR) CRITERION

Recently, the evaluation of control performances of Interconnected Power System has become an important issue with respect to the individual load–frequency controllers. Several performance measures are in practice like Area Control Error (ACE), Mutual Aid criterion (MAC) and Control Performance Standards (CPS). From literature it can be found that MAC is analogous to flat frequency control in which the tie-line power flow is restricted and in CPS approach the periodic monitoring and the control is based on that monitoring requires more skill which is a drawback of that approach. So this paper deals with the modified ACE approach i.e., AR approach.

The input signal to conventional area LFC is the linear combination of net area tie-line exchange and frequency deviations, called the Area Controller Error (ACE):

$$(ACE)_m = A_n = (P_{Tn} - P^r_{Tn}) + \beta_n(F - F^r) = \Delta P_{Tn} + \beta_n \Delta F_n \quad n = 1,2,\dots N,$$

(27)

With

$$P_{Tn} = \sum_{\alpha\in n} P_{T\alpha}$$

Where P_{Tn} is the total tie-line exchange of area n = 1,2,…., N and F is the common system frequency in N – area interconnection, P^r_{Tn} and F^r are reference values of the interchange and frequency schedules respectively, α is the number of inter area tie-lines, β_n is the frequency bias coefficient of n[th] area.

As the individual area LFC regulator is considered with PI controller, the required control input depends on the Area Requirement signal (AR_i)

$$(AR)_i = \Delta P_{di} = -\beta_n A_n - \frac{1}{T_{rn}}\int_0^t A_n dt + \Delta P^0_{dn}; i = n = 1,2,...N \quad (28)$$

Where T_{rn} is the parameters of the area n = 1,2,… N regulators, while Δp^0_{dn} is the initial condition of ΔP_{dn} and is assumed to be zero at time =0.

In classical realization of LFC is implicitly assumed that all tie-lines are lossless. Then, the absolute values of opposite direction power flows at two ends of any tie-line are taken as equal (outgoing+, ingoing-), i.e.,

$$P_{mn} = -P_{nm}; m,n \in I_k \quad (29)$$

Where I_k represents the set of all inter area tie-lines directly connected to an area k.

The consequence of eqn (29) for the whole interconnections is the relation

$$\sum_{n=1}^{N} P_{En} = 0, \quad (30)$$

Where the total area ‘n’ interchange is

$$P_{En} = \sum_{\alpha=1}^{t_k} P_\alpha$$

In computing Area Control Error (ACE), which is considered as the linear combination of change in frequency (βΔF) and change in tie-line power deviation (ΔP_{tie}) neglecting the effect of power loses in the tie-lines, since the measured interchanges at two ends of the same tie-line are of different absolute value. Then the equation (29) due to line losses, is not correct. Thus, the adopted assumption of lossless tie-lines, results to a systematic error, when calculating the (ACE) signals. The consequence is the deterioration of the basic LFC principle, that the maintenance at zero of ACEs in all control areas, leads to zero steady-state errors of all tie-line exchange and system frequency deviations, following a step-load disturbance in any area, enabling in the maintenance of net area power exchanges and system frequency on desired (scheduled, or reference) values. This causes the need for frequent corrections of accumulated synchronous time-errors and inadvertent interchanges when they reach the prescribed tolerance limits, even the average frequency is maintained within the prescribed ± 0.1Hz deviation limits, around the reference value. So sophisticated measuring techniques for tie-line losses is to be adopted by applying direct measurement of tie-line flows on both line ends and their transmission to the interested control centers. Then, these measurements are used for the modification of (ACE) control inputs of connected areas LFC schemes and is

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ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 3, September 2013

referred as Area Requirement (AR). The area requirement signal (28) is distributed and transmitted to all area regulating power plants and generators through commutation networks, to ensure the permanent area generation/consumption power balance in all areas and in the whole interconnection.

In this paper, the Area Requirement (AR) for i^{th} area is considered and as represented in equation (28).The schematic diagram representation of the Area Requirement for i^{th} area is shown in fig 5. Here, ΔP_{Ti} represents the sum of the tie-line flow sending from system i to the connected systems, K_{Ari} represents the frequency bias coefficient which is used to convert the frequency deviation into the electric power capacity and ΔF_i represents the frequency deviation and P_{ELDi} represents the total for the command values for economic load distribution and ΔP_{Di} is the load variation. ΔAR_i represents and instantaneous supply/demand imbalance in region i and is used as anLFC performance measure calculating the standard deviation and performing statistical processing.

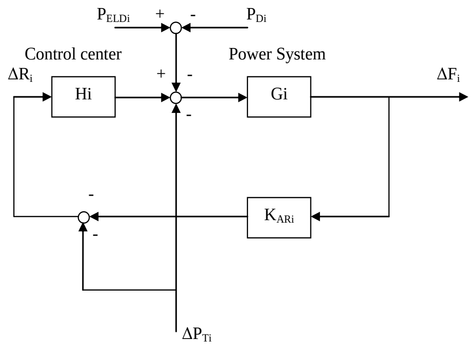

Fig. 5 Schematic diagram representation i^{th} Area's Requirement

A. Objective function

A performance index can be defined by the Integral Square Error (ISE) or cost function of the frequency deviation and tie line power. Accordingly, the objective function J is set to be [22]

$$J = \int_0^{\infty} [(\beta \Delta f_1)^2 + (\Delta P_{tie})^2]dt \qquad (31)$$

Based on this objective function J the optimization problem can be stated as: Minimize J subjective to:

$$K_p^{min} \le K_p \le K_p^{max}, K_I^{min} \le K_I \le K_I^{max} \qquad (32)$$

This study focuses on optimal tuning of controllers for the LFC and tie-power flow control BFO algorithm. The aim of the optimization is to search for the optimum controller parameters setting that maximize the minimum damping ratio of the system.

VIII. NORTH AMERICAN ELECTRIC RELIABILITY COUNCIL'S CONTROL PERFORMANCE STANDARDS

In 1997, the North American Electric Reliability Council (NERC) proposed new control performance standards [20,21] CPS1 and CPS2 to evaluate the control area performance in normal interconnected power system operation. Each control area is required to monitor its control performance and report its compliance CPS1 and CPS2 to NERC [22] at the end of each month.

A. Control Performance Standard 1 (CPS 1)

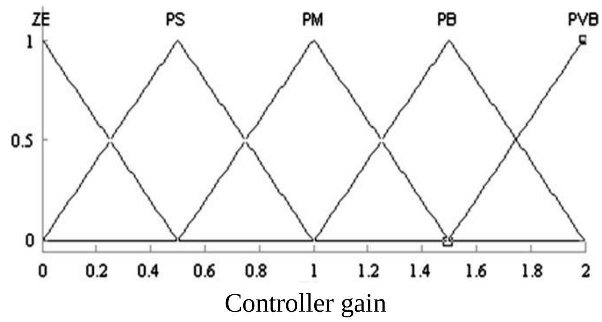

Fig. 6 Membership function for the controller outputs (αi).

Control Performance Standard 1 assesses the impact of Area Control Error on frequency over a certain period window or horizon and it is defined as follows: over a sliding certain period, the average of the "clock-min averages" of a control area's Area Control Error divided by "10 times its area frequency bias" times the corresponding "clock- min averages of the interconnection frequency error" shall be less than the square of a given constant ε_1, representing a target frequency bound. This is expressed [22]

$$\text{Avg}_{period}\left[\left(\frac{ACE_i}{-10\beta_i}\right)_1 \Delta F_i\right] \le \varepsilon_1^2 \qquad (33)$$

where ACE_i is the Clock-average of ACE, ΔF_i: the clock-min average of frequency deviation from schedule, βI is the frequency bias of the control area, ε_1: targeted frequency bound for CPS1, i: control area I and ε_1 is the clock 1- min average.

ε_1 is a constant derived the historical frequency record of a control area. It is the root mean square of one- min average frequency deviation from a schedule based on frequency performance over an averaging period of a year. The period (n) is defined as one year for control area evaluation or one month for the report of NERC. To calculate CPS1 (K_{CPS1}), a dimensionless compliance factor (K_{CF}) is defined as:

$$K_{CF} = \frac{\sum\left[\left(\frac{ACE_i}{-10\beta_i}\right)_1 \Delta F_1\right]}{n\varepsilon_1^2} \qquad (34)$$

CPS1 is then obtained from the following equation:

$$K_{CPS1} = (2-K_{CF})\ 100\% \qquad (35)$$

The fundamental requirement for CPS1 is that performance, as measured by percentage compliance must be at least 100%.

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ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 3, September 2013

1. When $K_{CPS1} \geq 200\%$, which means $K_{CF} \leq 0$, there is $\Sigma(ACE_1 * \Delta F_1) \leq 0$. Under this condition, ACE facilitates the frequency quality.

2. When $100\% \leq K_{CPS1} < 200\%$, which means $0 < K_{CF} \leq 1$, there is $0 \leq \Sigma\ [(ACE_i/-10\beta_i)_1 * \Delta F_1] \leq n\ \varepsilon_1^2$. The Control Performance Standard 1 standard is satisfied.

3. When $K_{CPS1} < 100\%$, which means $K_{CF} > 1$, there is $\Sigma[(ACE_i/-10\beta_i)_1 * \Delta F_1] > n\varepsilon_1^2$. ACE has exceeded the permitted range so that it has a bad effect on the frequency and quality of power grid.

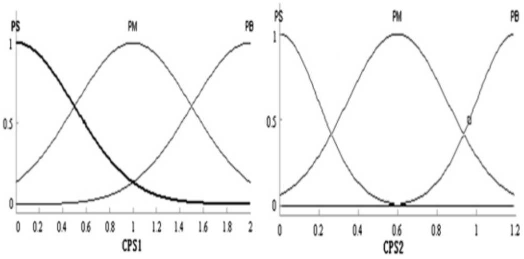

Fig. 7. Membership function for the input variables (CPS1, CPS2)

B. Control Performance Standard 2 (CPS 2)

The Control Performance Standard 2 (CPS2), limits the magnitude of short-term ACE values. It requires the 10-min averages of a control area's ACE be less than a given constant (L_{10}), as in the equation below:

$$AVG_{10min}(ACE_i) \leq L_{10} \quad (36)$$

Where, $L_{10} = 1.65\varepsilon_{10}\sqrt{(-10\beta_i)(-10\beta_s)}$. Note that β_s is the summation of the frequency bias settings of all control areas in the considered interconnection, and ε_{10} is the target frequency bound for CPS2. To comply with this standard, each control area must have its compliance no less than 90%. A compliance percentage is calculated from the following equation:

$$K_{CPS2} = \frac{Avg_{10min}(ACE_i)}{L_{10}} \quad (37)$$

In order to meet the requirements of the power grid frequency quality, the average ACE value during 10-min in each control region should be in the normal distribution as:

$$\sigma = \varepsilon_{10}\sqrt{(-10\beta_i)(-10\beta_s)}. \quad (38)$$

C. Optimization rules based on Control Performance Standards

The Suppose Control Performance Standard 1 $\geq$100% and Control Performance Standard 2 $\geq$ 90% should be the goal of the LFC control strategy.

D. Fuzzy logic design

Fuzzy logic rules are designed to manipulate the conventional proportional plus integral- type load frequency control to achieve the comply with NERC, s Control Performance Standard 1 and Control Performance Standard 2. The control structure for each area is

$$u_i = \Delta P_{ci} = \alpha K_p.ACE_i - \alpha K_i \int ACE_i dt \quad (39)$$

where ΔPC is the governor set point or raise /lower signal, K_p and K_i are proportional and integral control parameter and α is set using fuzzy logic and called fuzzy gain. This paper uses information that reflects compliance with CPS1 and CPS2 as the input to the fuzzy rules.

Fig.9. Dynamic responses of the frequency deviations of a two - area interconnected reheat power system with PI controller designed using AR criterion / CPS criterion for a step load disturbance of 1% in area 1.

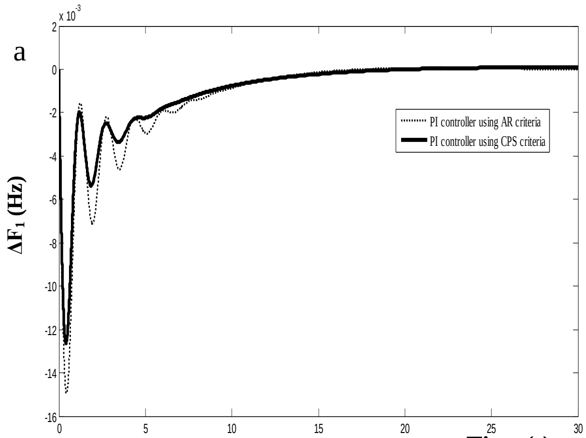

Fig 9 (a) ΔF$_1$ (Hz) Vs Time Time (s)

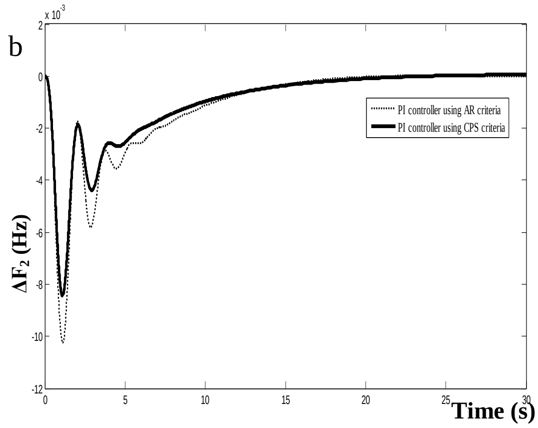

Fig 9 (b) ΔF$_2$ (Hz) Vs Time

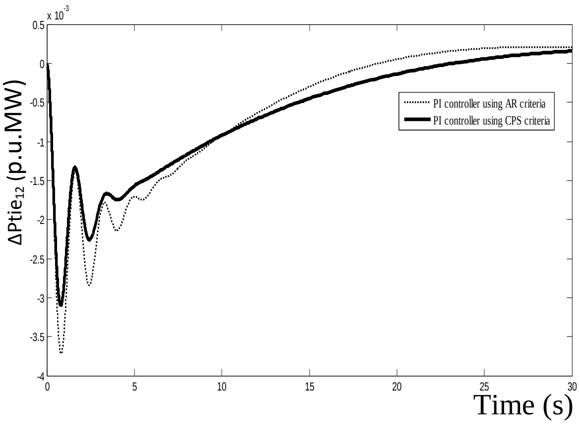

Fig.10. Dynamic responses of the tie - line power deviation of a two - area interconnected reheat power system with PI controller designed using AR criterion / CPS criterion for a step load disturbance of 1% in area 1.

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ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 3, September 2013

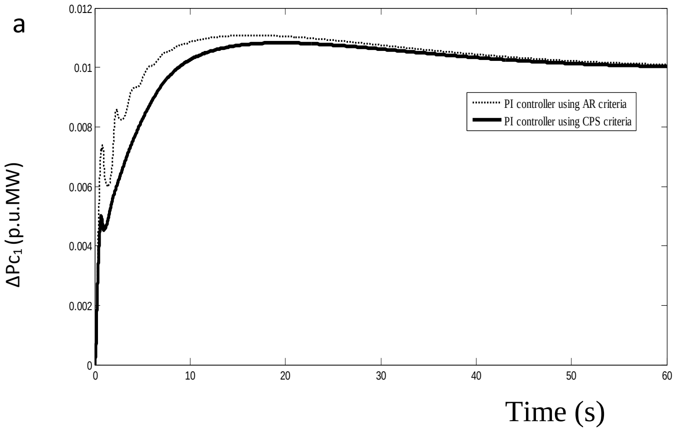

Fig 11 (a) ΔPc_1 (p.u.MW) Vs Time

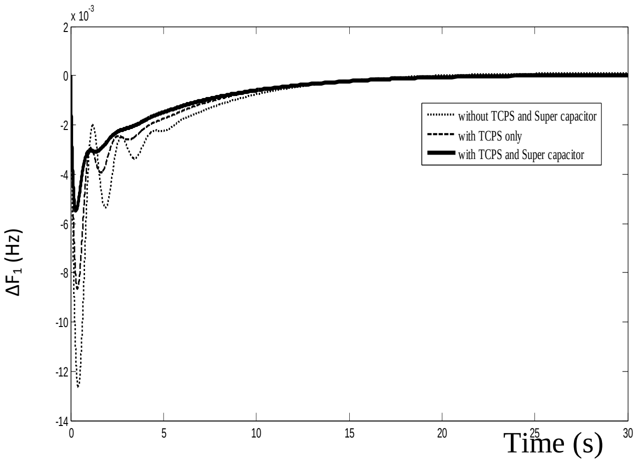

Fig 11 (b) ΔPc_2 (p.u.MW) Vs Time

Fig.11. Dynamic responses of the control input deviations of a two - area interconnected reheat power system with PI controller designed using AR criterion / CPS criterion for a step load disturbance of 1% in area 1.

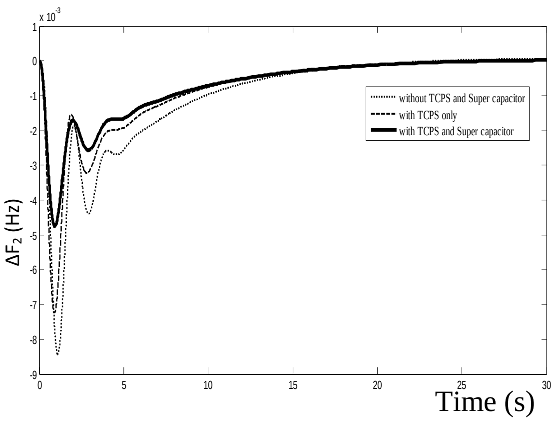

Fig 12 (a) ΔF_1 (Hz) Vs Time

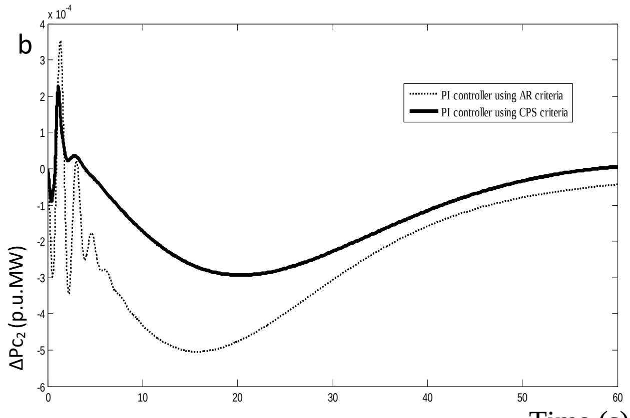

Fig 12. (b) ΔF_2 (Hz) Vs Time

Fig.12. Dynamic responses of the frequency deviations in a two-area interconnected reheat thermal power system considering CPS1 and CPS2 criterion without / with TCPS and SCES unit.

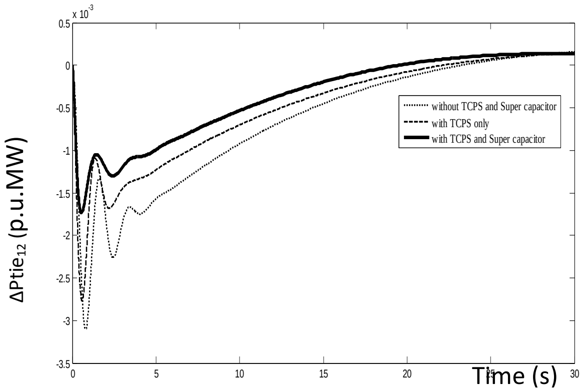

Fig.13. Dynamic responses of the Tie line power deviations in a two - area interconnected reheat thermal power system considering CPS1 and CPS2 criterion without / with TCPS and SCES units

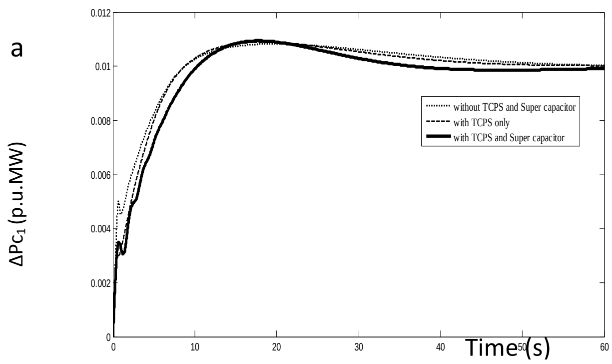

Fig. 14 (a) ΔPc_1 (p.u.MW) Vs Time

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Volume 3, Issue 3, September 2013

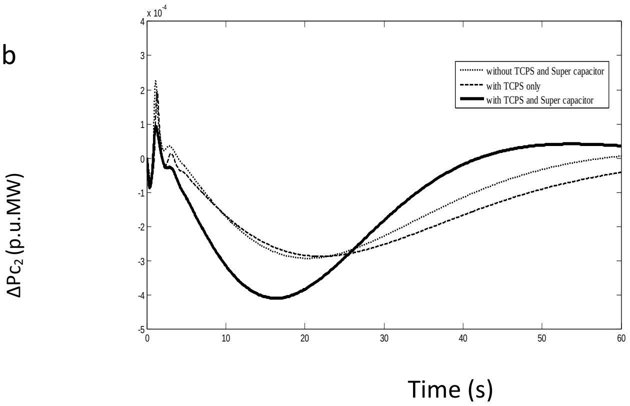

Fig. 14 (b) ΔPc_2 (p.u.MW) Vs Time

Fig.14. Dynamic responses of the control input deviations in a two area interconnected reheat thermal power system considering CPS1 and CPS2 criterion without/with TCPS and SCES units

Table 2: Optimized parameters of the two area interconnected power system.

The optimal parameters of PI controller for Two area interconnected reheat thermal power system with gas turbine in area-1 considering 0.01p.u.Mw step load disturbances in area -1	Area-1		Area-2	
	Proportional gain (K_{p1})	Integral Gain (K_{I1})	Proportional gain (K_{p2})	Integral Gain (K_{I2})
Area Requirement (AR) criterion	0.2555	0.3065	0.1977	0.1316
Control Performances Standards (CPS) criterion	0.2258	0.5321	0.1871	0.2526
With TCPS considering CPS criterion	0.2017	0.6065	0.1584	0.3252
With TCPS and Super Capacitor considering CPS criterion	0.1987	0.9623	0.1256	0.4681

Table 3: Comparison of the system performance for the four case studies

Two area interconnected reheat thermal power system with gas turbine in area-1 considering 0.01p.u.Mw step load disturbances in area-1	Setting time (τ_s) in sec			Peak over / under shoot		
	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1 in Hz	ΔF_2 in Hz	ΔP_{tie} in p.u MW
PI controller design based Area Requirement (AR) criterion	14.16	13.94	18.12	0.0148	0.0102	0.0036
PI controller design based Control Performance Standards (CPS) criterion	11.54	10.63	17.33	0.0124	0.0082	0.0031
PI controller design based Control Performance Standards (CPS) criterion considering TCPS in the Tie-line	8.92	7.95	12.24	0.0085	0.0071	0.0023
PI controller design based Control Performance Standards (CPS) criterion considering TCPS in the Tie-line and Super capacitor in area-1	6.58	6.45	10.05	0.0052	0.0046	0.0016

IX. SIMULATION RESULTS AND OBSERVATIONS

The optimal gains of Proportional plus Integral controllers (K_{p1}, K_{P2}, K_{I1}, K_{I2}) for the two case studies are obtained using BFO technique. These controllers are implemented in a two area multi unit power system without TCPS and SCES unit, with TCPS unit only, TCPS coordinated with SCES units. Relative compliance of the proposed controller based on LFC schemes using NERC standards have been established for the above system. CPS1 and CPS2 are considered as two inputs for the fuzzy logic controller and the fuzzy logic rules are framed according to their compliance.

From Tables 2 and 3 it can be observed that the controller designed using BFO algorithm for two area two unit thermal reheat power system with TCPS coordinated with SCES units have not only reduces the cost function but also ensure better stability, as this possess less over/ under shoot and faster settling time when compared with the output response of the system using the controller design for the two area multi unit thermal reheat power system without TCPS and SCES units.

The output responses of the two area multi unit interconnected power system are shown in figures 9 to 14 and from that it is evident that the dynamic responses of the two - area two - unit thermal reheat power system with TCPS coordinated with SCES units have improved significantly with the use of information that reflects compliance with CPS1 and CPS2.

X. CONCLUSION

In this paper, a sophisticated Load Frequency Control using Super Capacitor Energy Storage unit coordinated with Thyristor Controlled Phase Shifter has been proposed for a two area interconnected Reheat Thermal Power System. The BFO algorithm was employed to achieve the optimal parameters of the Proportional plus Integral gain values. This algorithm has faster converging algorithm and will reduce computational burden and was found to have superior solution quality in satisfying the objective. An Integral Square Error of the frequency deviation and tie-line power is taken as the objective function which is referred as cost function to improve the system response in terms of the settling time and overshoots. Simulation results reveal that the design concept for damping out the inertia mode and inter-area mode, the co-ordinated control is effective to suppress the frequency deviation of two area system simultaneously. It may be therefore be concluded that, the SCES unit with a sufficient margin of LFC capacity absorbs the speed governor capability in excess of falling short of the frequency bias value and tie-line power flow control by an Thyristor Controlled Phase Shifter be expected to be utilize as a new ancillary service for the stabilization of the tie-line power oscillations. More over simulation results emphasis that the PI Controller designed based Control Performance Standards (CPS) criteirion with SCES coordinated with TCPS unit using BFO Algorithm gives a superior damping performance for frequency and tie line power deviation compared to that of the simulation results obtained with the PI Controller for a two area interconnected Reheat Thermal Power System with TCPS.

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APPENDIX

(i) Data for Thermal Reheat Power System [3]

Rating of each area = 2000MW, Base power=2000 MVA, f°=60Hz, $K_{p1}=K_{p2}$=120Hz/p.u.MW $T_{p1}=T_{p2}$=20sec, $T_{t1}=T_{t2}=T_{t3}=T_{t4}$=0.3 sec, $T_{g1}=T_{g2}=T_{g3}=T_{g4}$ = 0.08sec,$K_{r1}=K_{r2}=K_{r3}=K_{r4}$=0.5, $T_{r1}=T_{r2}=T_{r1}=T_{r2}$ =10 sec, $R_1=R_2=R_3=R_4$ = 2.4Hz/p.u MW, a_{12}= -1, T_{12}=0.545 p.u MW/Hz, $\beta_1=\beta_2$ =0.425 p.u. MW/Hz, ΔP_{D1}=0.01p.u MW

(ii) Data for GT unit [6]

T_{GH} = 0.2 sec, X_G = 0.6 sec, Y_G = 1.1 sec C_g=1, b_g= 0.049 sec, T_F = 0.239 sec, T_{CR}=0.01 sec, T_{CD}=0.2 sec

(iii) Data for Super Capacitor Energy Storage unit [9]

K_{vd} = 0.1 kV/kA, K_0 = 70 kV/Hz, C = 1 F, R = 100Ω, K_{SCES}=0.7 Hz/pu Mw, T_{SCES} =0.01 sec

(iv) Data for TCPS [11]

$K\phi$=1.5 rad/Hz, ϕ_{max} = 10°, ϕ_{min} = -10°, Tps = 0.1sec

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International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 3, September 2013

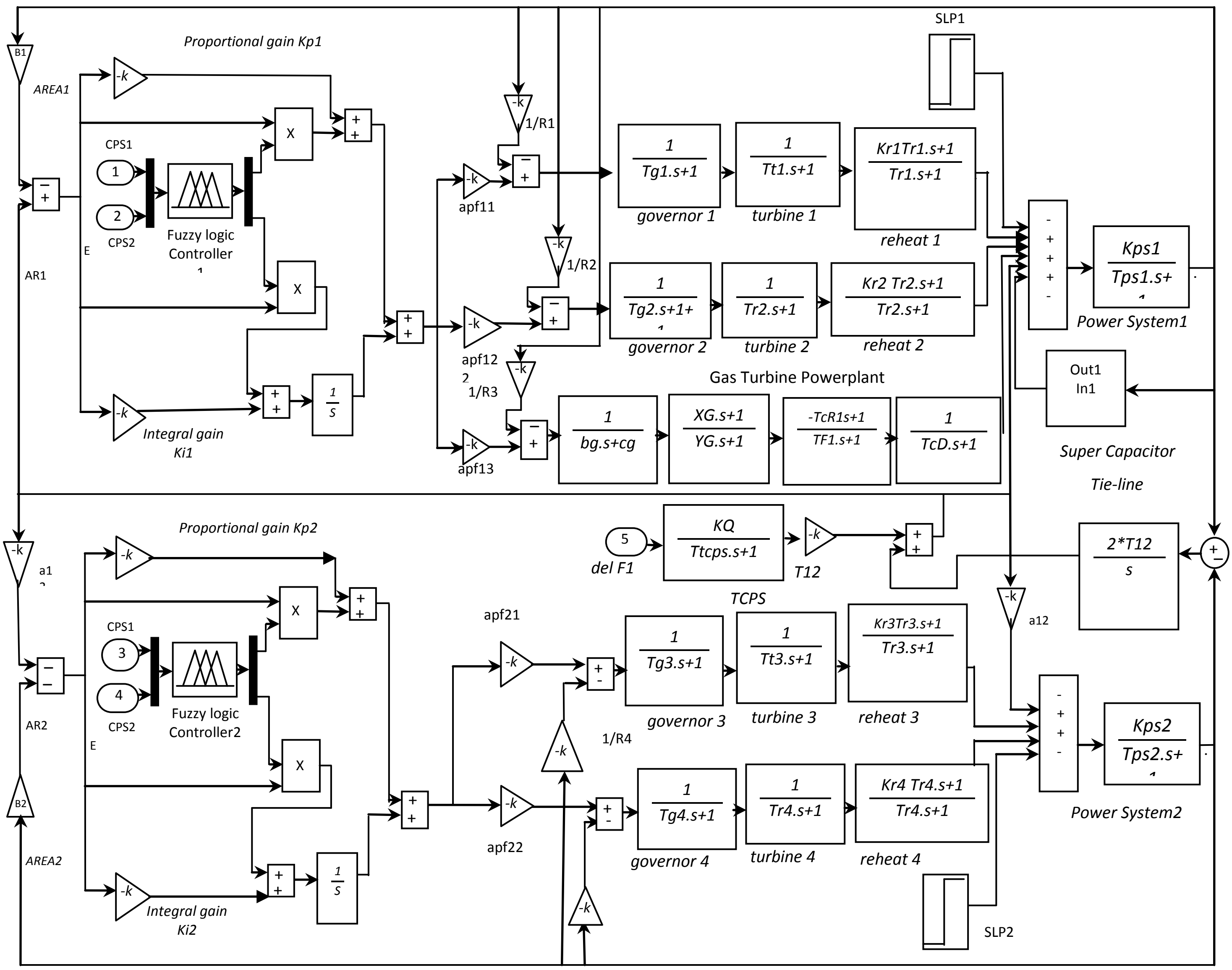

Fig. 8. Transfer function model of a two-area interconnected thermal reheat power system with TCPS and SCES units