Computation of Ancillary Service Requirement Assessment Indices for Load Frequency Control in a Restructured Power System using SMES Unit and SCES Unit

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Abstract: To ensure a quality power supply the power system should not only match the total generation with total load and the associated system losses but also should emphasis better Ancillary Services. Even small disturbances to the power system can result in wide deviation in system frequency and quick restoration process are of prime importance not only based on the time of restoration and also should ensure stability limits. This paper proposes various design procedures for computing Power System Ancillary Service Requirement Assessment Indices (PSASRAI) for a Two-Area Thermal Reheat Interconnected Power System (TATRIPS) in a restructured environment. As simple conventional Proportional plus Integral (PI) controllers are still popular in power industry for frequency regulation as in case of any change in system operating conditions new gain values can be computed easily even for multi-area power systems, this paper focus on the computation of various PSASRAI for Two Area Thermal Reheat Interconnected Power System in restructured environment based on the settling time and peak undershoot concepts of control input deviations of each area. Energy storage is an attractive option to augment demand side management implementation, so storage devices like Super Capacitor Energy Storage (SCES) and Superconducting Magnetic Energy Storage (SMES) unit can be efficiently utilized to meet the peak demand. So the design of the Proportional plus Integral (PI) controller gains for the restructured power system without and with the storage units are carried out using Bacterial Foraging Optimization (BFO) algorithm. 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. In this paper the PSASRAI are calculated for different types of possible transactions and the necessary remedial measures to be adopted are also suggested. If PSARAI based on settling time lies between 1 to 1.5 and if PSARAI based on peak undershoot is less than 0.2 distributed generation has to be incorporated and if the limit exceeds then the system becomes vulnerable and may result to black outs.

Keywords: Bacterial Foraging Optimization, Superconducting Magnetic Energy Storage, Super Capacitor Energy Storage, Proportional plus Integral Controller, Ancillary Service, Power System Ancillary Service Requirement Assessment Indices.

1. INTRODUCTION

As the power system network comprises of several control areas and the various areas are interconnected through tie-lines and the scheduled energy exchange between control areas is enhanced through tie-lines. A small load fluctuation in any area causes the deviation of frequencies of all the areas and also of the tie-line power flow. These deviations have to be corrected through various supplementary controls maintaining frequency and power interchanges with interconnected control areas at the scheduled values are the major objectives of a Load Frequency Control (LFC) problem [1, 2]. In a restructured power system the major change that had happened is with the emergence of Independent Power Producers (IPP) which can sell power to Vertically Integrated Utilities (VIU). In an interconnected power system, a sudden load perturbation in any area causes the deviation of frequencies of all the areas and also in the tie-line powers. This has to be corrected to ensure the generation and distribution of electric power companies to ensure good quality. This can be achieved by optimally tuning Load-Frequency controller gains. A number of control strategies have been employed in the design of load-frequency controllers in order to achieve better dynamic performance [3-7]. The efficient incorporation of controllers will modify the transient response and steady state error of the system. Among the various types of load-frequency controllers, the most widely employed is the conventional Proportional plus Integral controller (PI). Various studies have been made in connection with the LFC in a deregulated environment over last decades [8-11]. These studies try to modify the conventional LFC system to take into account the effect of bilateral contracts on the dynamics and improve the dynamical transient response of the system under various operating conditions especially with decentralized controllers. The importance of decentralized controllers for multi area load-frequency control in the restructured environment, where in, each area controller uses only the local states for feedback, is well known. The stabilization of frequency oscillations in an

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interconnected power system becomes challenging when implemented in the future competitive environment. So advanced economic, high efficiency and improved control schemes [12- 14] are required to ensure the power system reliability for which Ancillary Services have to be adopted. A fast acting Energy Storage units like SMES [15-19] and SCES [20-24] units can be adopted in effectively damping the electromechanical oscillations occurring in the power system, because they provide storage capacity in addition to the kinetic energy of the generator rotor which can share the sudden changes.

Ancillary services can be defined as a set of activities undertaken by generators, consumers and network service providers and coordinated by the system operator that have to maintain the availability and quality of supply at levels sufficient to validate the assumption of commodity like behaviour in the main commercial markets. There are different types of ancillary services such as voltage support, regulation, etc. The real power generating capacity related ancillary services, including Regulation Down Reserve (RDR), Regulation Up Reserve (RUR) in which regulation is the load following capability under Load Frequency Control (LFC) and Spinning Reserve (SR) is a type of operating reserve, which is a resource capacity synchronized to the system that is unloaded, is able to respond immediately to serve load, and is fully available within ten minutes but Non-Spinning Reserve (NSR) are the one in which NSR is not synchronized to the system and Replacement Reserve (RR) is a resource capacity non synchronized to the system, which is able to serve load normally within thirty or sixty minutes. Reserves can be provided by generating units or interruptible load in some cases. In this paper the most powerful evolutionary computational technique Bacterial Foraging Optimization (BFO) [25-27] 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. The algorithm is a computational intelligence based technique that is not affected larger by the size and nonlinearity of the problem and can be convergence to the optimal solution in many problems where most analytical methods fail to converge. Various methodologies were adopted in computing Power System Ancillary Service Requirement Assessment Indices (PSASRAI) for Two-Area Thermal Reheat Interconnected Power System (TATRIPS) in a restructured environment. With the various Power System Ancillary Service Requirement Assessment Indices (PSASRAI) like Feasible Assessment Indices (FAI), Feasible Service Requirement Assessment Indices (FASRAI) Comprehensive Assessment Indices (CAI) or Comprehensive Service Requirement Assessment Indices (CASRAI) the remedial measures to be taken can be adjudged like integration of additional spinning reserve, incorporation of effective intelligent controllers, load shedding etc. In the early stages of power system restoration, the black start units are of the greatest interest because they will produce power for the auxiliaries of the thermal units without black start capabilities. Under this situation a conventional frequency control i.e., a governor may no longer be able to compensate for sudden load changes due to its slow response. Therefore, in an inter area mode, damping out the critical electromechanical oscillations is to be carried out effectively in the restructured power system. Moreover, the system's control input requirement should be monitored and remedial actions to overcome the control input deviation excursions are more likely to protect the system before it enters an emergency mode of operation. Special attention is therefore given to the behaviour of network parameters, control equipments as they affect the voltage and frequency regulation during the restoration process which in turn reflects in PSASRAI.

2. MODELLING OF A TWO-AREA THERMAL REHEAT INTERCONNECTED POWER SYSTEM (TATRIPS) IN RETRUCTURED SCENARIO

In the restructured competitive environment of power system, the Vertically Integrated Utility (VIU) no longer exists. The deregulated power system consists of GENCOs, DISCOs, and Transmissions Companies (TRANSCOs) and Independent System Operator (ISO). GENCOs which will compete in a free market to sell the electricity they produce. With the emergence of the distinct identities of GENCOs, TRANSCOs, DISCOs and the ISO, many of the ancillary services of a VIU will have a different role to play and hence have to be modelled differently. Among these ancillary service controls one of the most important services to be enhanced is the Load-frequency control [18]. The LFC in a deregulated electricity market should be designed to consider different types of possible transactions, such as poolco-based transactions, bilateral transactions and a combination of these two [19, 20]. In the new scenario, a DISCO can contract individually with a GENCO for acquiring the power and these transactions will be made under the supervision of ISO. To make the visualization of contracts easier, the concept of "DISCO Participation Matrix" (DPM) is used which essentially provides the information about the participation of a DISCO in contract with a GENCO.

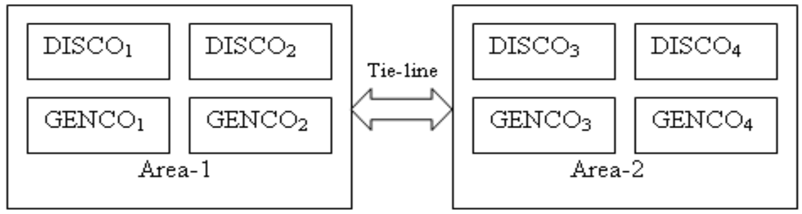

Figure 1: Schematic diagram of two-area system in restructured environment.

In DPM, the number of rows has to be equal to the number of GENCOs and the number of columns has to be equal to the number of DISCOs in the system. Any entry of this matrix is a fraction of total load power contracted by a DISCO toward a GENCO. As a results total of entries of column belong to DISCOi of DPM is $\sum_i cpf_{ij} = 1$. In this study two-area interconnected power system in which each area has two GENCOs and two DISCOs. Let GENCO 1, GENCO 2, DISCO 1, DISCO 2 be in area 1 and GENCO 3, GENCO 4, DISCO 3, DISCO 4 be in area 2 as shown in Figure **1**. The corresponding DPM is given as follows [4].

$$DPM = \begin{bmatrix} & DISCO & & \\ cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix} \begin{matrix} G \\ E \\ N \\ C \\ O \end{matrix} \quad (1)$$

Where *cpf* represents "Contract Participation Factor" and is like signals that carry information as to which the GENCO has to follow the load demanded by the DISCO. The actual and scheduled steady state power flow through the tie-line are given as

$$\Delta P_{tie1-2,\,scheduled} = \sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\Delta P_{L\,j} - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\Delta P_{L\,j} \quad (2)$$

$$\Delta P_{tie1-2,\,actual} = \left(2\pi T_{12}/s\right)\left(\Delta F_1 - \Delta F_2\right) \quad (3)$$

and at any given time, the tie-line power error $\Delta P_{tie1-2,\,error}$ is defined as

$$\Delta P_{tie1-2,\,error} = \Delta P_{tie1-2,\,actual} - \Delta P_{tie1-2,\,scheduled} \quad (4)$$

The error signal is used to generate the respective ACE signals as in the traditional scenario [6]

$$ACE_1 = \beta_1 \Delta F_1 + \Delta P_{tie\,1-2,\,error} \quad (5)$$

$$ACE_2 = \beta_2 \Delta F_2 + \Delta P_{tie\,2-1,\,error} \quad (6)$$

For two area system as shown in Figure **1**, the contracted power supplied by i[th] GENCO is given as

$$\Delta Pg_i = \sum_{j=1}^{DISCO=4} cpf_{i\,j}\Delta PL_j \quad (7)$$

Also note that $\Delta PL_{1,LOC} = \Delta PL_1 + \Delta PL_2$ and $\Delta PL_{2,LOC} = \Delta PL_3 + \Delta PL_4$. In the proposed LFC implementation, contracted load is fed forward through the DPM matrix to GENCO set points. The actual loads affect system dynamics *via* the input $\Delta PL_{,LOC}$ to the power system blocks. Any mismatch between actual and contracted demands will result in frequency deviations that will drive LFC to re dispatch the GENCOs according to ACE participation factors, i.e., apf_{11}, apf_{12}, apf_{21} and apf_{22}. The state space representation of the minimum realization model of 'N' area interconnected power system may be expressed as [14].

$$\begin{aligned} \dot{x} &= Ax + Bu + \Gamma d \\ y &= Cx \end{aligned} \quad (8)$$

Where $x = [x_1^T, \Delta p_{ei} \dots x_{(N-1)}^T, \Delta p_{e(N-1)} \dots x_N^T]^T$, n-state vector

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

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

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

$y = [y_1 \dots y_N]^T$, $2N$ - 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 consisting of load changes.

3. MODELLING OF ENERGY STORAGE SYSTEM (ESS)

3.1. Modelling of Energy Storage (SMES) Unit

Superconducting Magnetic Energy Storage (SMES) device is a DC current device that stores energy in the magnetic field. SMES is suggested as storage unit for improving the dynamic performance of power system. However, a small rating Superconducting Magnetic Energy Storage (SMES) can effectively damp out the power frequency oscillations caused by small perturbations to the load. A SMES is capable of controlling active and reactive power simultaneously has been expected as one if the most effective stabilizers for power oscillations.

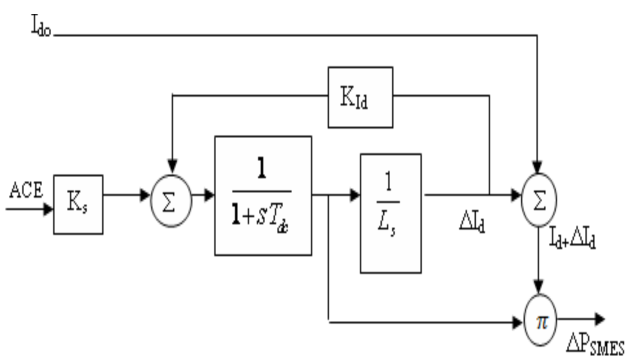

Figure 2: Block diagram representation of SMES unit.

Figure **2** shows the block diagram representation of the SMES unit. To achieve quick restoration of the current, the inductor current deviation can be sensed and used as a negative feedback signal in the SMES control loop [15]. In a two-area interconnected thermal restructured power system under with the sudden small disturbances which continuously disturb the normal operation of power system. As a result the requirement of frequency controls of areas beyond the governor capabilities SMES is located in area 1 absorbs and supply required power to compensate the load fluctuations. Tie-line power flow monitoring is also required in order to avoid the blackout of the power system. The schematic diagram in Figure **3** shows the configuration of a thyristor controlled SMES unit. The SMES unit contains DC superconducting Coil and converter which is connected by Y–D/Y–Y transformer. The inductor is initially charged to its rated current I_{do} by applying a small positive voltage. Once the current reaches the rated value, it is maintained constant by

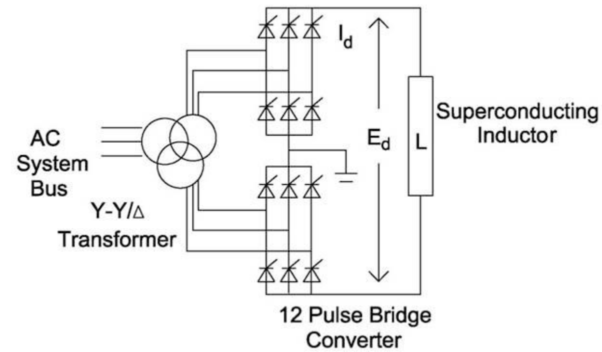

Figure 3: Schematic diagram of SMES unit.

reducing the voltage across the inductor to zero since the coil is superconducting. Neglecting the transformer and the converter losses, the DC voltage is given by

$$E_d = 2V_{do}\cos\alpha - 2I_d R_c \tag{9}$$

Where Ed is DC voltage applied to the inductor, firing angle (α), I_d is current flowing through the inductor. R_c is equivalent commutating resistance and V_{do} is maximum circuit bridge voltage. Charge and discharge of SMES unit are controlled through change of commutation angle α. In LFC operation, the dc voltage E_d across the superconducting inductor is continuously controlled depending on the sensed Area Control Error (ACE) signal. Moreover, the inductor current deviation is used as a negative feedback signal in the SMES control loop. So, the current variable of SMES unit is intended to be settling to its steady state value. If the load is used as a negative feedback signal in the SMES control demand changes suddenly, the feedback provides the prompt restoration of current. The inductor current must be restored to its nominal value quickly after a system disturbance, so that it can respond to the next load disturbance immediately. As a result, the energy stored at any instant is given by

$$W_{sm} = W_{smo} + \int_{t^0}^{t} P_{sm}(\tau)d\tau \tag{10}$$

Where, W_{smo} = 1/2 LI_{do}^2, initial energy in the inductor. Equations of inductor voltage deviation and current deviation for each area in Laplace domain are as follows

$$\Delta E_{di}(s) = \left(\frac{K_{\text{SMES}}}{1+sT_{dci}}\right)\left[\beta_1 \Delta F_1(s) + \Delta P_{tie1}(s)\right] - \frac{K_{id}}{1+sT_{dci}}\Delta I_{di}(s) \tag{11}$$

$$\Delta I_{di}(s) = (1/sL_i)\,\Delta E_{di}(s) \tag{12}$$

Where, ΔE_{di}(s)-converter voltage deviation applied to inductor in SMES unit, K_{SMES}-Gain of the control loop SMES, T_{dci} -converter time constant in SMES unit, K_{id} - gain for feedback ΔI_{di} in SMES unit., ΔI_{di}(s)- inductor current deviation in SMES unit. The deviation in the inductor real power of SMES unit is expressed in time domain as follows [30].

$$\Delta P_{SMES\ i} = \Delta E_{di}\ I_{doi} + \Delta I_{di}\ \Delta E_{di} \tag{13}$$

3.2. Modelling of Super Capacitor Energy Storage (SCES) Unit

A super-capacitor is an electrochemical device consisting of two porous electrodes, an ion-exchange membrane separating the two electrodes and a potassium hydroxide electrolyte. In many ways, a SCES or Ultra Capacitor (UC) has similarities as a standard capacitor but can have 100–1000 times the capacitance per unit volume compared to a conventional electrolytic capacitor. Super-capacitors offer high values of power density and energy density compared, respectively, to batteries and conventional capacitors. They can be charged /discharged faster as compared to batteries and conventional capacitors. Moreover they are capable of cycling millions of times and are thus virtually maintenance free and have much longer lifetime. All these attributes of super-capacitors make them ideal for improved load frequency control in interconnected power systems. As the governor control mechanism starts working to set the power system to the new equilibrium condition the Super Capacitor stores back its nominal energy. Similar is the action when there is a sudden decrease in load demand. Thus SCES unit immediately absorbs some portion of the excess energy in the system and as the system returns to its steady state the excess energy is released by SCES unit to the system and the stored energy again attains its nominal value. Figure **4** shows the proposed configuration of super-capacitor system in each control area of the power system. The Voltage Source Converter (VSC) consists of a 6-pulse, pulse width modulated (PWM) rectifier/inverter using insulated gate bipolar junction transistors. The PWM converter and the dc–dc buck boost chopper are linked by a dc link capacitor. The dc voltage across the dc link capacitor is kept constant throughout by a 6-pulse PWM converter [23, 24]. The bidirectional dc–dc converter is operated in boost mode if the electric power is to be supplied to the super capacitor bank from the power system.

The block diagram representation of SCES unit is shown in Figure **5**. Either frequency deviation or Area Control Error (ACE) can be used as the control signal to the CES unit ($\Delta error_i = \Delta f_i$ or ACE_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., $\Delta error_i = \Delta f_i$) of the power system is used as the control signal to CES, then the deviation in the current, ΔI_{di} is given by [23].

The power flow in the capacitor at any instant is

$$P_d = E_d\ I_d \tag{14}$$

The initial power flow into the capacitor is

$$P_{d0} = E_{d0}\ I_{d0} \tag{15}$$

E_{d0} and I_{d0} are the magnitudes of voltage and current prior to the load disturbance. When a load disturbance occurs, the power flow into the coil is

$$P_{d0} + \Delta P_d = \left(E_{d0} + \Delta E_d\right)\left(I_{d0} + \Delta I_d\right) \tag{16}$$

so that the incremental power change in the capacitor is

$$\Delta P_d = \left(I_{d0}\Delta E_d + \Delta E_d \Delta I_d\right)\left(I_{d0} + \Delta I_d\right) \tag{17}$$

The term $E_{d0}.I_{d0}$ is neglected since $E_{d0} = 0$ in the storage mode to hold the rated voltage at constant value.

$$\Delta I_{di} = \left[\frac{1}{1+sT_{DCi}}\right]\left[K_{CESi}\ \Delta F_i - K_{vdi}\ \Delta E_{di}\right] \tag{18}$$

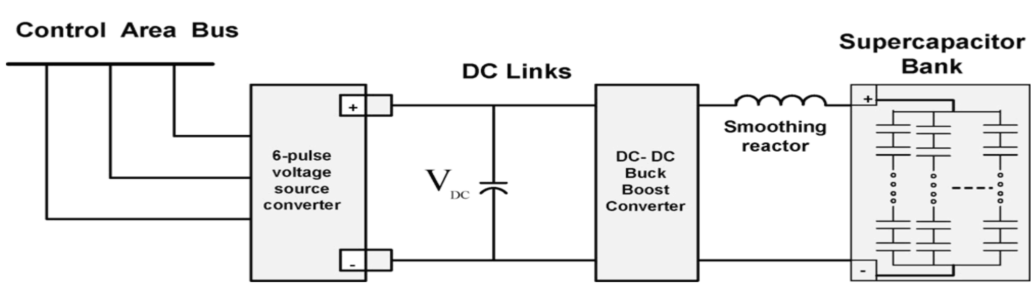

Figure 4: Configuration of super-capacitor bank in control area.

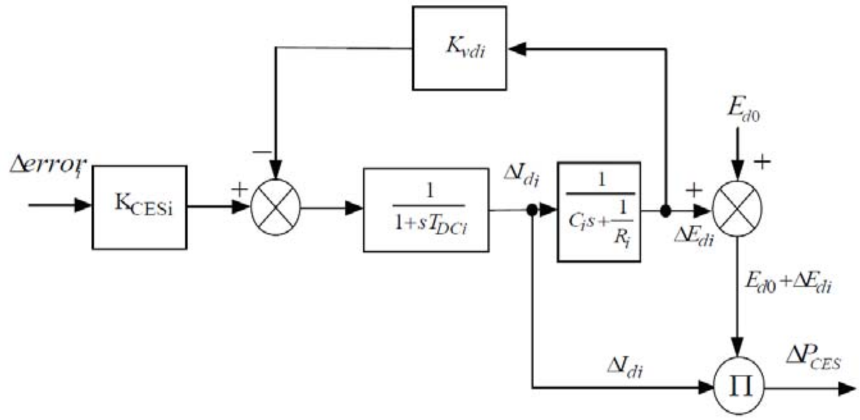

Figure 5: Block diagram with capacitor voltage deviation feedback.

If the tie-line power flow deviations can be sensed, then the Area Control Error (ACE) can also be fed to the CES as the control signal (i.e., $\Delta error_i = ACE_i$). Being a function of tie-line power deviations, ACE as the control signal to CES, will further improve the tie-power oscillations. Thus, ACE of the two areas are given by

$$ACE_i = B_i \Delta F_i + \Delta P_{tie-i\,j} \text{ ; i, j=1,2} \tag{19}$$

Where $\Delta P_{tie\ ij}$ is the change in tie-line power flow out of area i to j.

Thus, if ACE_i is the control signal to the CES, then the deviation in the current ΔI_{di} would be

$$\Delta I_{di} = \left[\frac{1}{1+sT_{DCi}}\right]\left[K_{CESi}\ \ \Delta ACE_i - K_{vdi}\ \ \Delta E_{di}\right] \text{ i, j= 1, 2} \tag{20}$$

4. DESIGN OF PI CONTROLLERS USING BACTERIAL FORAGING OPTIMIZATION (BFO) TECHNIQUE

The proportional plus integral controller gain values (K_{pi}, K_{Ii}) are tuned based on the settling time of the output response of the system (especially the frequency deviation) using Bacterial Foraging Optimization (BFO) technique. The closed loop stability of the system with decentralized PI controllers is assessed using settling time of the system output response [25]. It is observed that the system whose output response settles fast will have minimum settling time based criterion [26] and can be expressed as

$$F\,(K_p, K_i) = \min\ (\zeta_{si}) \tag{21}$$

$$U_1 = -K_{p1}\ ACE_1 - K_{I1}\int ACE_1 \quad dt \tag{22}$$

$$U_2 = -K_{p1}\ ACE_2 - K_{I1}\int ACE_2 \quad dt \tag{23}$$

Where, K_p is the Proportional gain K_I is the Integral gain; *ACE* is the Area Control Error*; U* is the Control input requirement of the respective areas. ζ_{si} is the settling time of the frequency deviation of the i[th] area under disturbance. The relative simplicity of this controller is a successful approach towards the zero steady state error in the frequency of the system. With the optimized gain values the performance of the system is analysed and various PSRAI are computed**.** The BFO method was introduced by Passino [25] motivated by the natural selection which tends to eliminate the animals with poor foraging strategies and favour those having successful foraging strategies. The foraging strategy is governed by four processes namely Chemotaxis, Swarming, Reproduction and Elimination and Dispersal. 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. To represent a tumble, a unit length random direction $\phi(j)$ is generated. Let, *"j"* is the index of chemotactic step, *"k"* is reproduction step and "*l*" is the elimination dispersal event. $\theta_i(j,k,l)$, is the position of i^{th} bacteria at j^{th} chemotactic step k^{th} reproduction step and l^{th} elimination dispersal event. The position of the bacteria in the next chemotactic step after a tumble is given by

$$\theta^i(j+1,\ \ k,\ \ l) = \theta^i(j,\ \ k,\ \ l) + C\,(\,i\,)\ \phi\,(\,j\,) \tag{24}$$

If the health of the bacteria improves after the tumble, the bacteria will continue to swim to the same direction for the specified steps or until the health degrades. Bacteria exhibits swarm behaviour i.e. healthy bacteria try to attract other bacterium so that together they reach the desired location (solution point) more rapidly. The effect of swarming [26] is to make the bacteria congregate into groups and moves as concentric patterns with high bacterial density. Mathematically swarming behaviour can be modeled

$$J_{cc}\left(\theta, P\left(j,k,l\right)\right)=\sum_{i=1}^{S} J^{i}cc\left(\theta,\theta^{i}\left(j.k.l\right)\right)$$
$$=\sum_{i=1}^{S}\left[-d_{attract}\exp\left(-\omega_{attract}\right)\sum_{m=1}^{p}\left(\theta^{m}-\theta^{i}_{m}\right)^{2}\right] \quad (25)$$
$$+\sum_{i=1}^{S}\left[-h_{repelent}\exp\left(-w_{repelent}\right)\sum_{m=1}^{p}\left(\theta^{m}-\theta^{i}_{m}\right)^{2}\right]$$

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, $d_{attract}$, $\omega_{attract}$, $h_{repelent}$, $\omega_{repelent}$ - different co-efficients representing the swarming behaviour of the bacteria which are to be chosen properly. In Reproduction step, population members who have sufficient nutrients will reproduce and the least healthy bacteria will die. The healthier population replaces unhealthy bacteria which get eliminated owing to their poorer foraging abilities. This makes the population of bacteria constant in the *evolution* process. In this 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 behaviour of stagnation i.e., being trapped in a premature solution point or local optima. The flow chat of BFO algorithm is shown in Figure **6**.

5. SIMULATION RESULTS AND OBSERVATIONS

In Figure **7** shows Simulink model of a Two- Area Thermal Reheat Interconnected Power System (TATRIPS) in restructured environment with SMES or SCES unit. The nominal parameters are given in Appendix. The Proportional plus Integral controller gains (K_p K_i) are tuned with BFO algorithm by optimizing the objective function (21) for the various case studies. The results are obtained by MATLAB 7.01 software and 100 iterations are chosen for the convergence of the solution in the BFO algorithm. These PI controllers are implemented in a Two-Area Thermal Reheat Interconnected restructured Power System with either SMES unit or SCES unit considering different utilization of capacity (K=0, 0.25, 0.5, 0.75, 1.0) and for different type of transactions. The corresponding frequency deviations Δf, tie- line power deviation ΔP_{tie} and control input deviations ΔP_c are obtained with respect to time as shown in Figure **8**. Simulation results reveal that the proposed PI controller for LFC system and coordinated with SCES units greatly reduces the peak over shoot / under shoot of the frequency deviations and tie- line power flow

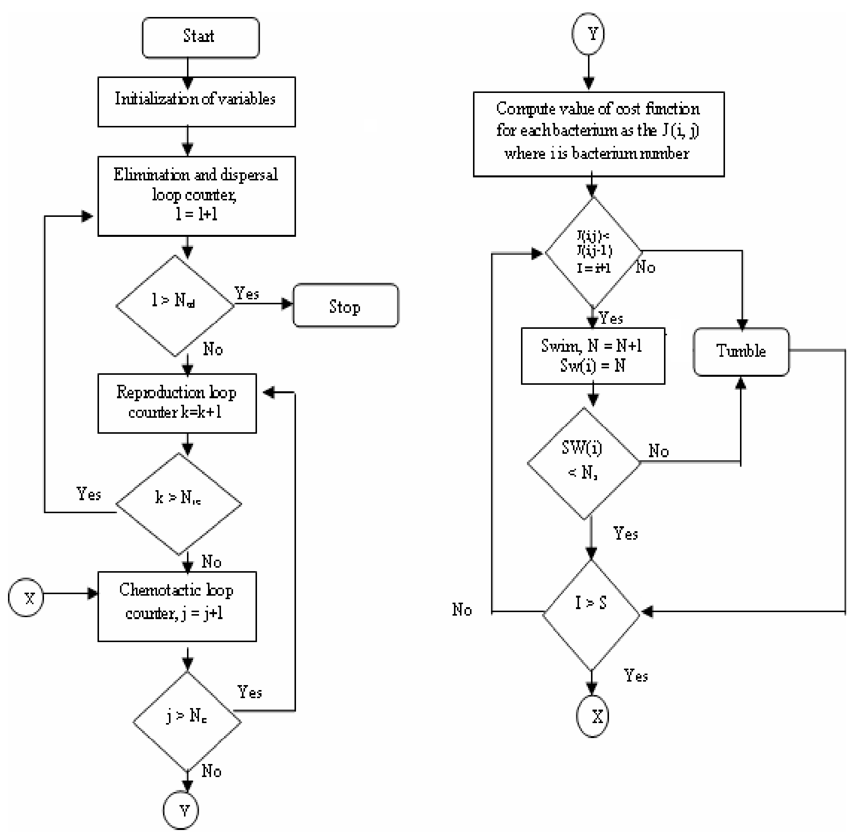

Figure 6: Flowchart for BFO algorithm.

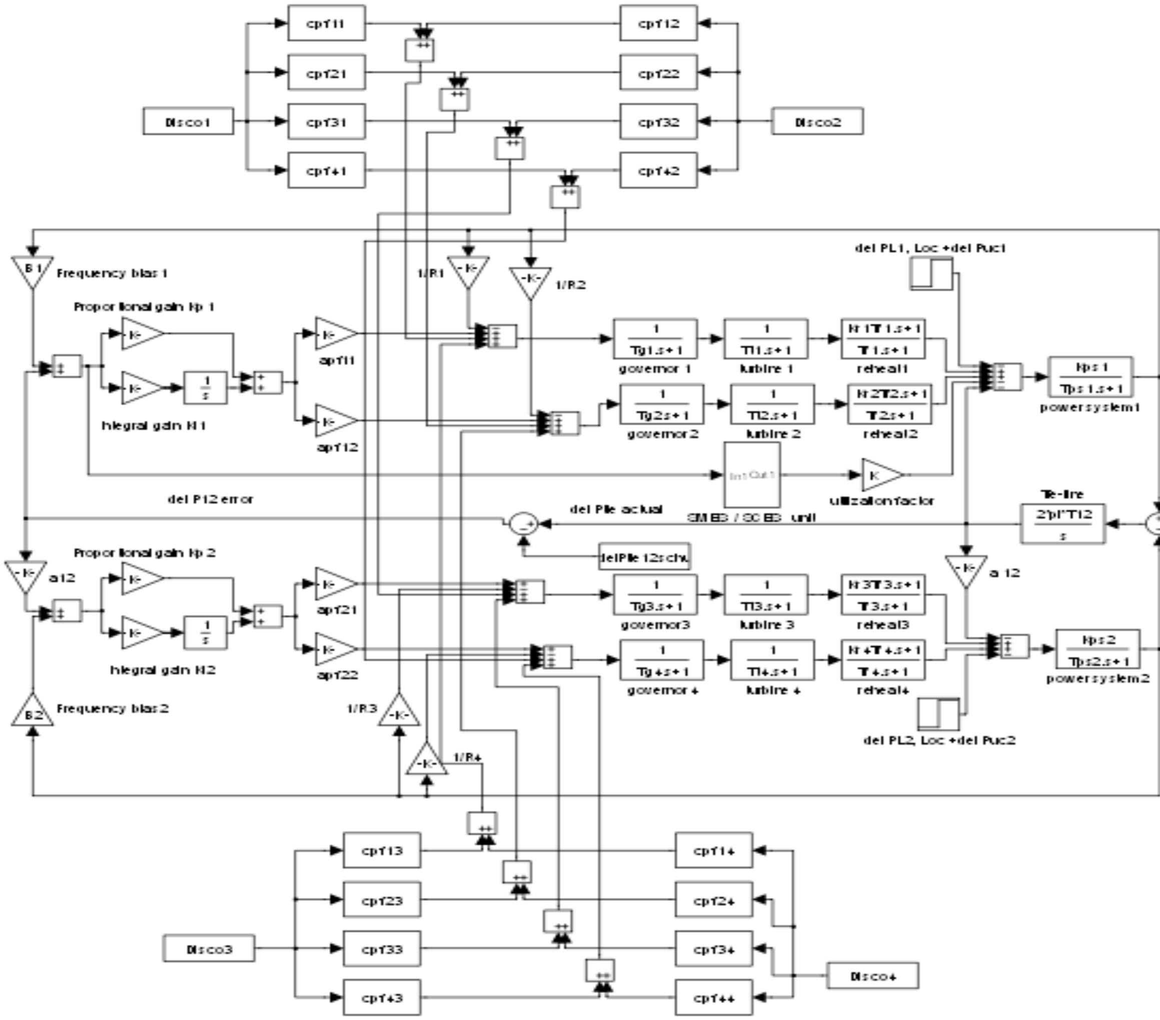

Figure 7: Simulink model of a Two- Area Thermal Reheat Interconnected Power System (TATRIPS) in restructured environment with SMES or SCES unit.

deviation. And also it reduces the control input requirements and the settling time of the output responses also reduced considerably. Moreover Power System Ancillary Service Requirement Assessment Indices (PSASRAI) namely, Feasible Assessment Indices (FAI) when the system is operating in a normal condition with both units in operation and Comprehensive Assessment Indices (CAI) are one or more unit outage in any area are obtained as discussed. In this study GENCO-4 in area 2 is outage are considered. From these Assessment Indices indicates the restorative measures like the magnitude of control input requirement, rate of change of control input requirement can be adjudged.

5.1. Feasible Restoration Indices

Scenario 1: Poolco based transaction

The optimal Proportional plus Integral (PI) controller gains are obtained for TATIPS considering various case studies for framing the Feasible Assessment Indices (FAI) which were obtained based on Area Control Error (ACE) as follows:

Case 1: In the TATRIPS considering both areas have two thermal reheat units. Consider a case where the GENCOs in each area participate equally in LFC and the load change occurs only in area 1. It denotes that the load is demanded only by DISCO 1 and DISCO 2. Let the value of this load demand be 0.1 p.u MW for each of them i.e. ΔPL_1= 0.1 p.u MW, ΔPL_2= 0.1 p.u MW, $\Delta PL_3 = \Delta PL_4$= 0.0. DISCO Participation Matrix (DPM) referring to Eq (26) is considered as [4]

$$DPM = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad (26)$$

As DISCO 3 and DISCO 4 do not demand power from any GENCOs the corresponding contract participation factors (columns 3 and 4) are zero. DISCO 1 and DISCO 2 demand identically from their local GENCOs, viz., GENCO 1 and GENCO 2. Therefore, $cpf_{11}=cpf_{12}=0.5$ and $cpf_{21}=cpf_{22}=0.5$. The frequency deviations (ΔF), tie-line power deviation (ΔP_{tie}) and control input requirements deviations (ΔP_c) of both areas are as shown the Figure **8**. The settling time (ς_s) and peak over /under shoot (*Mp*) of the control input deviations (ΔP_c) in both the area were obtained from Figure **8**. From the Figure **8d** and **e** the corresponding Feasible Assessment Indices $FAI_1,\ FAI_2,\ FAI_3\ and\ FAI_4$ are calculated as follows

Step 6.1 The Feasible Assessment Index 1 (ε_1) is obtained from the ratio between the settling time of the control input deviation $\Delta P_{c1}(\varsigma_{s1})$ response of area 1 and power system time constant (T_{p1}) of area 1

$$FRI_1 = \frac{\Delta P_{c1}(\varsigma_{s1})}{T_{p1}} \tag{27}$$

Step 6.2 The Feasible Assessment Index 2 (ε_2) is obtained from the ratio between the settling time of the control input deviation $\Delta P_{c2}(\varsigma_{s2})$ response of area 2 and power system time constant (T_{p2}) of area 2

$$FRI_2 = \frac{\Delta P_{c2}(\varsigma_{s2})}{T_{p2}} \tag{28}$$

Step 6.3 The Feasible Assessment Index 3 (ε_3) 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 $\Delta P_{c1}(\varsigma_s)$

$$FRI_3 = \Delta P_{c1}(\varsigma_p) - \Delta P_{c1}(\varsigma_s) \tag{29}$$

Step 6.4 The Feasible Assessment Index 4 (ε_4) is obtained from the peak value of the control input deviation $\Delta P_{c2}(\varsigma_p)$ response of area 1 with respect to the final value $\Delta P_{c2}(\varsigma_s)$

$$FRI_4 = \Delta P_{c2}(\varsigma_p) - \Delta P_{c2}(\varsigma_s) \tag{30}$$

Case 2: This case is also referred a Poolco based transaction on TATRIPS where in the GENCOs in each area participate not equally in LFC and load demand is more than the GENCO in area 1 and the load demand change occurs only in area 1. This condition is indicated in the column entries of the DPM matrix and sum of the column entries is more than unity.

Case 3: It may happen that a DISCO violates a contract by demanding more power than that specified in the contract and this excess power is not contracted to any of the GENCOs. This uncontracted power must be supplied by the GENCOs in the same area to the DISCO. It is represented as a local load of the area but not as the contract demand. Consider scenario-1 again with a modification that DISCO 1 demands 0.1 p.u MW of excess power i.e., $\Delta Puc_{,1}$= 0.1 p.u MW and $\Delta Puc_{,2}$ = 0.0 p.u MW. The total load in area 1 = Load of DISCO 1+Load of DISCO 2 = $\Delta PL_1 + \Delta Puc_1 + \Delta PL_2$ =0.1+0.1+0.1 =0.3 p.u MW.

Case 4: This case is similar to Case 2 to with a modification that DISCO 3 demands 0.1 p.u MW of excess power i.e., $\Delta Puc_{,2}$ = 0.1 p.u MW and., $\Delta Puc_{,1}$ = 0 p.u MW. The total load in area 2 = Load of DISCO 3+Load of DISCO 4 = $\Delta PL_1 + \Delta PL_2 + \Delta Puc_2$ =0+0+0.1 = 0.1 p.u MW.

Case 5: In this case which is similar to Case 2 with a modification that DISCO 1 and DISCO 3 demands 0.1 p.u MW of excess power i.e., $\Delta Puc_{,1}$= 0.1 p.u MW and $\Delta Puc_{,2}$ = 0.1 p.u MW. The total load in area 1 = Load of DISCO 1+Load of DISCO 2 = $\Delta PL_1 + \Delta Puc_1 + \Delta PL_2$ =0.1+0.1+0.1 = 0.3 p.u MW and total demand in area 2 = Load of DISCO 3+Load of DISCO 4 = $\Delta PL_3 + \Delta Puc_2 + \Delta PL_4$ =0+0.1+0 = 0.1 p.u MW

Scenario 2: Bilateral Transaction

Case 6: Here all the DISCOs have contract with the GENCOs and the following DISCO Participation Matrix (DPM) be considered [1- 4].

$$DPM = \begin{bmatrix} 0.4 & 0.25 & 0.2 & 0.4 \\ 0.3 & 0.15 & 0.1 & 0.2 \\ 0.1 & 0.4 & 0.3 & 0.25 \\ 0.2 & 0.2 & 0.4 & 0.15 \end{bmatrix} \tag{31}$$

In this case, the DISCO 1, DISCO 2, DISCO 3 and DISCO 4, demands 0.15 p.u MW, 0.05 p.u MW, 0.15 p.u MW and 0.05 p.u MW from GENCOs as defined by *cpf* in the DPM matrix and each GENCO participates in LFC as defined by the following ACE participation

Table 1a: Feasible Assessment Indices (FAI) with SMES / SCES Unit (Utilization Factor K=1) for TATRIPS

TATRIPS	Feasible Assessment Indices (FAI) based on control input deviations (ΔP_c) with SMES unit					Feasible Assessment Indices (FAI) based on control input deviations (ΔP_c) with SCES unit				
	ε_1	ε_2	ε_3	ε_4	$\int P_{SMES}$	ε_1	ε_2	ε_3	ε_4	$\int P_{SCES}$
Case 1	0.925	0.825	0.118	0.019	0.096	0.853	0.782	0.101	0.011	0.456
Case 2	0.947	0.859	0.175	0.022	0.112	0.861	0.801	0.123	0.013	0.496
Case 3	0.985	0.925	0.199	0.032	0.128	0.874	0.912	0.132	0.018	0.511
Case 4	0.951	1.225	0.151	0.061	0.101	0.951	0.982	0.136	0.021	0.524
Case 5	1.175	1.261	0.271	0.073	0.132	1.117	1.105	0.242	0.053	0.423
Case 6	0.825	0.775	0.135	0.087	0.148	0.814	0.724	0.113	0.064	0.478
Case 7	0.978	0.904	0.189	0.092	0.193	0.912	0.895	0.164	0.081	0.512
Case 8	0.991	1.011	0.287	0.094	0.207	0.954	0.987	0.211	0.088	0.507
Case 9	0.912	1.153	0.201	0.177	0.174	0.906	1.089	0.186	0.154	0.587
Case 10	1.075	1.126	0.312	0.187	0.233	1.012	1.113	0.289	0.162	0.611

Table 1b: Feasible Assessment Indices (FAI) with SMES / SCES Unit (Utilization Factor K=0.75) for TATRIPS

TATRIPS	Feasible Assessment Indices (FAI) based on control input deviations (ΔP_c) with SMES unit					Feasible Assessment Indices (FAI) based on control input deviations (ΔP_c) with SCES unit				
	ε_1	ε_2	ε_3	ε_4	$\int P_{SMES}$	ε_1	ε_2	ε_3	ε_4	$\int P_{SCES}$
Case 1	0.946	0.842	0.124	0.021	0.076	0.889	0.804	0.108	0.015	0.412
Case 2	0.961	0.873	0.181	0.028	0.081	0.894	0.823	0.131	0.019	0.423
Case 3	0.993	0.946	0.201	0.041	0.079	0.898	0.936	0.145	0.022	0.496
Case 4	1.024	1.254	0.164	0.063	0.086	0.989	0.997	0.152	0.026	0.511
Case 5	1.243	1.279	0.281	0.075	0.104	1.212	1.125	0.261	0.058	0.401
Case 6	0.849	0.873	0.142	0.089	0.079	0.828	0.796	0.134	0.068	0.425
Case 7	0.984	0.908	0.195	0.094	0.193	0.954	0.902	0.178	0.087	0.489
Case 8	1.029	1.015	0.297	0.096	0.112	0.962	0.992	0.232	0.092	0.474
Case 9	0.972	1.211	0.213	0.181	0.081	0.954	1.096	0.192	0.169	0.512
Case 10	1.215	1.236	0.328	0.189	0.113	1.105	1.135	0.291	0.175	0.543

Table 1c: Feasible Assessment Indices (FAI) with SMES / SCES Unit (Utilization Factor K=0.5) for TATRIPS

TATRIPS	Feasible Assessment Indices (FAI) based on control input deviations (ΔP_c) with SMES unit					Feasible Assessment Indices (FAI) based on control input deviations (ΔP_c) with SCES unit				
	ε_1	ε_2	ε_3	ε_4	$\int P_{SMES}$	ε_1	ε_2	ε_3	ε_4	$\int P_{SCES}$
Case 1	0.951	0.851	0.128	0.024	0.052	0.891	0.812	0.114	0.016	0.406
Case 2	0.984	0.888	0.196	0.029	0.057	0.923	0.848	0.137	0.023	0.413
Case 3	0.996	0.971	0.207	0.043	0.071	0.935	0.948	0.148	0.025	0.486
Case 4	1.037	1.278	0.178	0.064	0.048	0.991	0.998	0.158	0.027	0.504
Case 5	1.312	1.284	0.284	0.078	0.076	1.223	1.136	0.275	0.061	0.397
Case 6	0.868	0.874	0.145	0.091	0.054	0.834	0.812	0.137	0.074	0.418
Case 7	0.991	0.911	0.198	0.096	0.058	0.969	0.906	0.182	0.092	0.442
Case 8	1.124	1.017	0.309	0.097	0.075	0.973	0.997	0.241	0.094	0.424
Case 9	0.996	1.309	0.214	0.182	0.055	0.961	1.122	0.197	0.171	0.487
Case 10	1.263	1.316	0.332	0.191	0.076	1.139	1.141	0.298	0.178	0.498

Table 1d: Feasible Assessment Indices (FAI) with SMES / SCES Unit (Utilization Factor K=0.25) for TATRIPS

TATRIPS	Feasible Assessment Indices (FAI) based on control input deviations (ΔP_c) with SMES unit					Feasible Assessment Indices (FAI) based on control input deviations (ΔP_c) with SCES unit				
	ε_1	ε_2	ε_3	ε_4	$\int P_{SMES}$	ε_1	ε_2	ε_3	ε_4	$\int P_{SCES}$
Case 1	0.964	0.865	0.131	0.025	0.027	0.894	0.824	0.118	0.021	0.368
Case 2	0.997	0.894	0.208	0.029	0.031	0.933	0.854	0.167	0.024	0.384
Case 3	0.999	0.984	0.252	0.044	0.037	0.989	0.957	0.198	0.032	0.396
Case 4	1.041	1.299	0.188	0.065	0.025	0.995	0.999	0.162	0.048	0.489
Case 5	1.400	1.361	0.296	0.081	0.038	1.325	1.178	0.276	0.069	0.367
Case 6	0.891	0.874	0.146	0.093	0.028	0.848	0.824	0.141	0.078	0.401
Case 7	0.998	0.914	0.211	0.096	0.193	0.984	0.908	0.194	0.094	0.425
Case 8	1.128	1.021	0.314	0.099	0.038	0.982	0.999	0.268	0.096	0.414
Case 9	0.998	1.311	0.215	0.183	0.028	0.974	1.145	0.201	0.181	0.464
Case 10	1.283	1.324	0.338	0.193	0.039	1.241	1.196	0.301	0.189	0.471

factor apf_{11} = apf_{12} = 0.5 and apf_{21} = apf_{22} = 0.5. From this dynamic responses the corresponding $FAI_1,\ FAI_2,\ FAI_3$ *and* FAI_4 are calculated.

Case 7: For this case also bilateral transaction on TATRIPS is considered with a modification that the GENCOs in each area participate not equally in LFC and load demand is more than the GENCO in both the areas. But it is assumed that the load demand change occurs in both areas and the sum of the column entries of the DPM matrix is more than unity.

Case 8: Considering in the case 7 again with a modification that DISCO 1 demands 0.1 p.u MW of excess power i.e., ΔPuc_1=0.1 p.u.MW and ΔPuc_2=0.0 p.u MW. The total load in area 1 = Load of DISCO 1+Load of DISCO 2 = ΔPL_1 + ΔPuc_1+ΔPL_2 =0.15+0.1+0.05 =0.3 p.u MW and total load in area 2=Load of DISCO 3+Load of DISCO 4 = ΔPL_3 +ΔPL_4 =0.15+0.05 =0.2 p.u MW

Case 9: In the case which similar to case 7 with a modification that DISCO 3 demands 0.1 p.u.MW of excess power i.e., $\Delta Puc_{,2}$ = 0.1 p.u MW. The total load in area 1 = Load of DISCO 1+Load of DISCO 2 = ΔPL_3 +ΔPL_4 =0.15+0.05 =0.2 p.u.MW and total demand in area 2 = Load of DISCO 3+Load of DISCO 4 = ΔPL_3 +ΔPL_4 + ΔPuc_3 =0.15+0.05+0.1 =0.3 p.u MW

Case 10: In the case which similar to case 7 with a modification that DISCO 1 and DISCO 3 demands 0.1 p.u MW of excess power i.e., $\Delta Puc,_1$= 0.1 p.u MW and $\Delta Puc_{,2}$ = 0.1 p.u MW. The total load in area 1 = Load of DISCO 1 + Load of DISCO 2 = ΔPL_1 + ΔPuc_1 +ΔPL_2 = 0.15+0.1+0.05 = 0.3 p.u MW and total load in area 2 = Load of DISCO 3 + Load of DISCO 4 = ΔPL_3 + ΔPuc_3 +ΔPL_4 =0.15+0.1+0.05 = 0.3 p.u MW. For the Cases 1-10, Feasible Assessment Indices ($FAI_1,\ FAI_2,\ FAI_3,$ *and* FAI_4) or $\varepsilon_{1,}\ \varepsilon_2, \varepsilon_3$ *and* ε_4 are calculated are tabulated in Table **1**.

5.2. Comprehensive Assessment Indices

Apart from the normal operating condition of the TATRIPS few other case studies like one unit outage in an area, outage of one distributed generation in an area are considered individually. With the various case studies and based on their optimal gains the corresponding CAI is obtained as follows.

Case 11: In the TATRIPS considering all the DISCOs have contract with the GENCOs but GENCO4 is outage in area-2. In this case, the DISCO 1, DISCO 2, DISCO 3 and DISCO 4, demands 0.15 p.u MW, 0.05 p.u MW, 0.15 pu.MW and 0.05 pu.MW from GENCOs as defined by *cpf* in the DPM matrix (26). The output power of the GENCO 4 = 0.0 p.u MW.

Case 12: Consider in this case which is same as Case 11 but DISCO 1 demands 0.1 p.u MW of excess power i.e., ΔPuc_1= 0.1 p.u.MW and ΔPuc_2 = 0.0 p.u MW. The total load in area 1 = Load of DISCO 1+Load of DISCO 2= ΔPL_1 + ΔPuc_1+ΔPL_2 =0.15+0.1+0.05 =0.3 p.u MW and total load in area 2 = Load of DISCO 3+Load of DISCO 4 = ΔPL_3 +ΔPL_4 =0.15+0.05 =0.2 p.u MW.

Case 13: This case is same as Case 11 with a modification that DISCO 3 demands 0.1 p.u MW of excess power i.e., ΔPuc_3 = 0.1 p.u MW. The total load

Table 2a: Comprehensive Assessment Indices (CAI) with SMES / SCES Unit (Utilization Factor K=1) for TATRIPS

TATRIPS	Comprehensive Assessment Indices (CAI) based on control input deviations (ΔP_c) with SMES unit					Comprehensive Assessment Indices (CAI) based on control input deviations (ΔP_c) with SCES unit				
	ε_5	ε_6	ε_7	ε_8	$\int P_{SMES}$	ε_5	ε_6	ε_7	ε_8	$\int P_{SCES}$
Case 11	1.034	1.362	0.326	0.267	0.165	1.011	1.258	0.307	0.242	0.468
Case 12	1.134	1.454	0.371	0.312	0.229	1.098	1.361	0.323	0.306	0.564
Case 13	1.017	1.575	0.409	0.443	0.196	1.009	1.436	0.391	0.427	0.496
Case 14	1.468	1.659	0.415	0.506	0.259	1.441	1.564	0.398	0.488	0.568

Table 2b: Comprehensive Assessment Indices (CAI) with SMES / SCES Unit (Utilization Factor K=0.75) for TATRIPS

TATRIPS	Comprehensive Assessment Indices (CAI) based on control input deviations (ΔP_c) with SMES unit					Comprehensive Assessment Indices (CAI) based on control input deviations (ΔP_c) with SCES unit				
	ε_5	ε_6	ε_7	ε_8	$\int P_{SMES}$	ε_5	ε_6	ε_7	ε_8	$\int P_{SCES}$
Case 11	1.087	1.381	0.341	0.277	0.195	1.033	1.341	0.311	0.255	0.411
Case 12	1.231	1.479	0.352	0.318	0.209	1.114	1.424	0.328	0.311	0.498
Case 13	1.129	1.615	0.411	0.457	0.146	1.024	1.512	0.394	0.428	0.487
Case 14	1.483	1.659	0.426	0.508	0.221	1.471	1.623	0.402	0.491	0.507

Table 2c: Comprehensive Assessment Indices (CAI) with SMES / SCES Unit (Utilization Factor K=0.5) for TATRIPS

TATRIPS	Comprehensive Assessment Indices (CAI) based on control input deviations (ΔP_c) with SMES unit					Comprehensive Assessment Indices (CAI) based on control input deviations (ΔP_c) with SCES unit				
	ε_5	ε_6	ε_7	ε_8	$\int P_{SMES}$	ε_5	ε_6	ε_7	ε_8	$\int P_{SCES}$
Case 11	1.092	1.391	0.343	0.283	0.125	1.068	1.356	0.321	0.264	0.347
Case 12	1.336	1.481	0.358	0.327	0.184	1.204	1.468	0.336	0.318	0.401
Case 13	1.246	1.618	0.421	0.457	0.112	1.098	1.569	0.409	0.437	0.398
Case 14	1.507	1.688	0.432	0.509	0.206	1.488	1.645	0.414	0.501	0.425

Table 2d: Comprehensive Assessment Indices (CAI) with SMES or SCES Unit (Utilization Factor K=0.25) for TATRIPS

TATRIPS	Comprehensive Assessment Indices (CAI) based on control input deviations (ΔP_c) with SMES unit					Comprehensive Assessment Indices (CAI) based on control input deviations (ΔP_c) with SCES unit				
	ε_5	ε_6	ε_7	ε_8	$\int P_{SMES}$	ε_5	ε_6	ε_7	ε_8	$\int P_{SCES}$
Case 11	1.098	1.421	0.345	0.289	0.112	1.082	1.369	0.332	0.278	0.312
Case 12	1.428	1.491	0.367	0.334	0.164	1.298	1.474	0.342	0.327	0.384
Case 13	1.282	1.621	0.428	0.464	0.101	1.259	1.581	0.411	0.445	0.362
Case 14	1.565	1.693	0.444	0.511	0.201	1.551	1.674	0.427	0.509	0.394

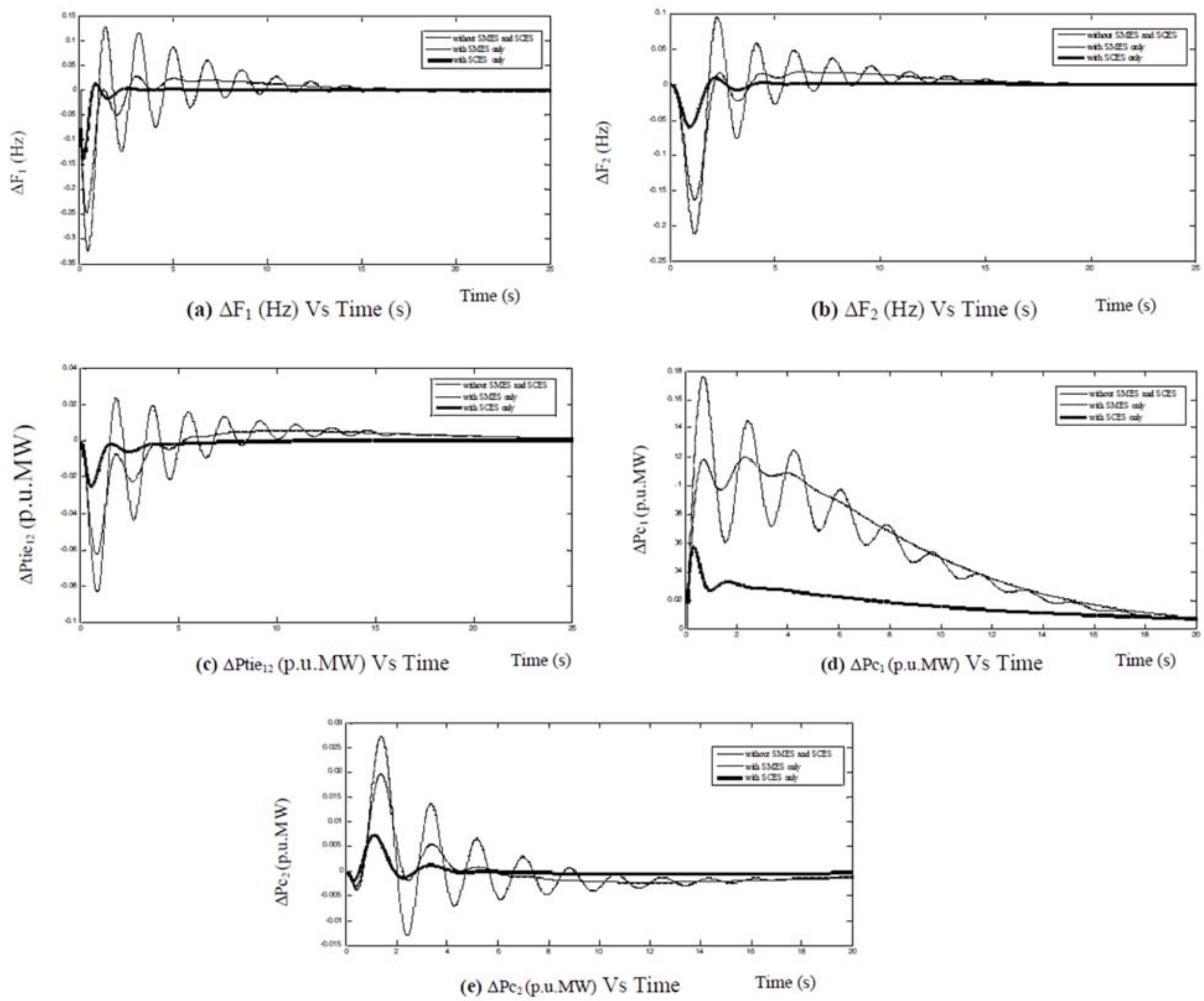

Figure 8: Dynamic responses of the frequency deviations, tie- line power deviations and Control input deviations for TATRIPS in the restructured scenario-1 (poolco based transactions).

in area 1 = Load of DISCO 1+Load of DISCO 2 = $\Delta PL_3 + \Delta PL_4$ =0.15+0.05 =0.2 p.u MW and total demand in area 2 = Load of DISCO 3+Load of DISCO 4 = $\Delta PL_3 + \Delta PL_4 + \Delta Puc_3$ =0.15+0.05+0.1 =0.3 p.u MW

Case 14: In this case which is similar to Case 11 with a modification that DISCO 1 and DISCO 3 demands 0.1 p.u MW of excess power i.e., ΔPuc_1= 0.1 p.u.MW and ΔPuc_3=0.1 p.u MW. The total load in area 1=Load of DISCO 1+Load of DISCO 2=$\Delta PL_1+\Delta Puc_1+\Delta PL_2$ = 0.15+0.1+0.05 = 0.3 p.u MW and total load in area 2 = Load of DISCO 3+Load of DISCO 4 = $\Delta PL_3 + \Delta Puc_3 + \Delta PL_4$ =0.15+0.1+0.05 = 0.3 p.u MW.

For the Case 11-14, the corresponding Assessment Indices are referred as Comprehensive Assessment Indices ($CAI_1, CAI_2, CAI_3, and\ CAI_4$) are obtained as $\varepsilon_5, \varepsilon_6, \varepsilon_7\ and\ \varepsilon_8$ and $\int P$ is the ancillary service requirement for various case studies are tabulated in Table **2**.

5.3. Power System Ancillary Service Requirement Assessment Indices (PSASRAI)

5.3.1 Based on Settling Time

(i) If $\varepsilon_1, \varepsilon_2, \varepsilon_5, \varepsilon_6 \geq 1$ then the integral controller gain of each control area has to be increased causing the speed changer valve to open up widely. Thus the speed- changer position attains a constant value only when the frequency error is reduced to zero.

(ii) If $1.0 < \varepsilon_1, \varepsilon_2, \varepsilon_5, \varepsilon_6 \leq 1.5$ then more amount of distributed generation requirement is needed. Energy storage is an attractive option to augment demand side management implementation by ensuring the Ancillary Services to the power system.

(iii) If $\varepsilon_1, \varepsilon_2, \varepsilon_5, \varepsilon_6 \geq 1.5$ then the system is vulnerable and the system becomes unstable and may even result to blackouts.

5.3.2. Based on Peak Undershoot

(i) If $0.15 \leq \varepsilon_3, \varepsilon_4, \varepsilon_7, \varepsilon_8 < 0.2$ then Energy Storage Systems (ESS) for LFC is required as 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. A fast-acting energy storage system in addition to the kinetic energy of the generator rotors is advisable to damp out the frequency oscillations.

(ii) If $0.2 \leq \varepsilon_3, \varepsilon_4, \varepsilon_7, \varepsilon_8 < 0.3$ then more amount of distribution generation requirement is required or Energy Storage Systems (ESS) coordinated control with the FACTS devices are required for the improvement relatively stability of the power system in the LFC application and the load shedding is also preferable

(iii) If $\varepsilon_3, \varepsilon_4, \varepsilon_7, \varepsilon_8 > 0.3$ then the system is vulnerable and the system becomes unstable and may result to blackout.

6. CONCLUSION

This paper proposes the design of various Power System Ancillary Service Requirement Assessment Indices (PSASRAI) which highlights the necessary requirements to be adopted in minimizing the control input deviations there by reducing the frequency deviations, tie-line power deviation in a two-area Thermal reheat interconnected restructured power system to ensure the reliable operation of the power system. The PI controllers are designed using BFO algorithm and implemented in a TATRIPS without and with SMES or SCES units. The BFO Algorithm was employed to achieve the optimal parameters of gain values of the various combined control strategies. As BFO is easy to implement without additional computational complexity, with this algorithm quite promising results can be obtained and ability to jump out the local optima. Moreover, Power flow control using SCES unit is found to be efficient and effective for improving the dynamic performance of load frequency control of the interconnected power system than that of the system with SMES unit. From the simulated results it is observed that the restoration indices calculated for the TATRIPS with SCES unit indicates that more sophisticated control for a better restoration of the power system output responses and to ensure improved Power System Ancillary Service Requirement Assessment Indices (PSASRAI) in order to provide good margin of stability.

APPENDIX – A

(i) Data for Thermal Reheat Power System [13]

Rating of each area = 2000 MW, Base power = 2000 MVA, f^o = 60 Hz, $R_1 = R_2 = R_3 = R_4$ = 2.4 Hz / p.u.MW, $T_{g1} = T_{g2} = T_{g3} = T_{g4}$ = 0.08 s, $T_{r1} = T_{r2} = T_{r1} = T_{r2}$ = 10 s, $T_{t1} = T_{t2} = T_{t3} = T_{t4}$ = 0.3 s, $K_{p1} = K_{p2}$ = 120Hz/p.u.MW, $T_{p1} = T_{p2}$ = 20 s, $\beta_1 = \beta_2$ = 0.425 p.u.MW / Hz, $K_{r1} = K_{r2} = K_{r3} = K_{r4}$ = 0.5, $2\pi T_{12}$ = 0.545 p.u.MW / Hz, a_{12} = -1.

(ii) Data for the SMES unit [15]

I_{d0} = 4.5 kA, L = 2.65 H, K_o = 6000 kV/Hz, $K_{i\,d}$ = 0.2 kV/kA, K_{SMES} = 100 KV/ unit MW, T_{dc}= 0.03s

(iii) Data for Super Capacitor Energy Storage unit [22, 23]

T_{SCES} =0.01 sec, K_{vd} =0.1 KV / KA, Ko = 70 KV/Hz, T_{DC}= 0.055, C = 1 F, R= 100ohm, E_{do} =2 kV

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