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# ABC Algorithm based Load- Frequency Controller for an interconnected Power System Considering nonlinearities and Coordinated with UPFC and RFB

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***Abstract*— The design of Load Frequency Control (LFC) system plays a vital role in automation of power system. This paper proposes a sophisticated application of Redox Flow Batteries (RFB) coordinated with Unified Power Flow Controller (UPFC) for the improvement of Load Frequency Control of a multi- unit multi- area power system. Governor Dead Band (GDB) and Generation Rate Constraints (GRC) are also considered in the investigations. The UPFC offers an effective means to enhance improvement in the power transfer capability of the tie-line. The main application of UPFC is to stabilize the frequency oscillations of the inter-area mode in the interconnected power system by the dynamic control of tie-line power flow. The Redox flow batteries, which are not aged to the frequent charging and discharging, have a quick response and outstanding function during overload conditions. In addition to leveling load, the battery is advantageous for secondary control in the power system and maintenance of power quality of distributed power resources. The Artificial Bee Colony (ABC) algorithm is used to optimize the parameters of the cost functions along with the integral controller. Simulation studies reveal that the frequency control concept and control design of a RFB coordinated with UPFC units enhance the inertia centre mode as well as inter-area oscillation modes in terms of peak deviations and settling time as compared to the output responses of the system obtained without UPFC and RFB units.***

***Index Terms*—Artificial Bee Colony, Governor Dead Band, Generation Rate Constraints, Redox Flow Batteries, Unified Power Flow Controller..**

## I. INTRODUCTION

The Load Frequency Control system should maintain the system frequency and the tie-line power flow close to the scheduled values. For the past several decades, lot of work pertaining to the design of classical controllers for interconnected power systems [1, 2] has been carried-out and in most of the cases, the mathematical model has been over simplified by ignoring the simultaneous presence of important system nonlinearities such as Governor Dead Band (GDB) and Generation Rate Constraints (GRC). All governors in the thermal reheat power system have dead bands like mechanical friction, backlash, valve overlaps in hydraulic relays, which are important for speed control even under small disturbances. So, the speed governor dead band has significant effect on the dynamic performance of load-frequency control system. Moreover, the GDB has a destabilizing effect on the transient response of the system [3]. In a power system, another most important constraint on modern large size thermal units is the stringent generation rate constraint *i.e.* the power generation can change only at a specified maximum rate. The GRC of the system is considered by adding a limiter to the control system [4]. In this condition, the response will be with larger overshoots and longer settling times when compared with the system where GRC is not considered. So, if the parameters of the controllers are not chosen properly, the system may become unstable. In the simultaneous presence of GDB and GRC, even with small load perturbation, the system becomes highly nonlinear and hence the optimization problem becomes rather complex [5]. Even though many control strategies have been efficiency in the design of load-frequency controller for interconnected power systems considering GDB and GRC nonlinearities [3-5] because of the future vast competitive environment, the stabilization of frequency oscillations in the interconnected power system becomes challenging. So advanced economic, high efficiency and improved control schemes are required to ensure the power system reliability. As an interconnected power system is subjected to a large load change, conventional load-frequency controller, i.e. governor, may not be rapidly able to damp large frequency oscillation due to its slow response [6]. To overcome this problem, a high speed response compensator should be used [7]. The recent advances in power electronics have led to the development of the Flexible Alternating Current Transmission Systems (FACTS). These FACTS devices are capable of controlling the network condition in a very fast manner and because of this reason the usage of FACTS devices are more apt to improve the stability of power system. In recent years, as a innovative research basis new FACTS devices are being introduced to increase power system operations flexibility and controllability, to enhance system stability and to achieve better utilization of existing power system [8].The Unified Power Flow Controller (UPFC) is member of the FACTS family with very attractive features [9],which are able to control, simultaneously or selectively, all the parameters (voltage, impedance and phase angle) affecting power flow in the transmission line . UPFC which consists of a series and shunt converter connected by a common dc link capacitor can simultaneously perform the function of transmission line real and active power flow control in addition to UPFC bus voltage /shunt reactive power control [10]. The shunt

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converter of the UPFC controls the UPFC bus voltage/shunt reactive power and dc link capacitor voltage. The series converter of the UPFC controls the transmission line real and active power flows by injecting a series voltage of adjustable magnitude and phase angle [11]. On the other hand the series part known as Static Synchronous Series Compensator (SSSC) can be controlled without restrictions. The phase angle of series voltage can be chosen independently from line current between 0 to 2$\pi$, and its magnitude is variable between zero and a defined maximum value. The parallel part known as Static synchronous Compensator (STATCOM), injects an almost sinusoidal current of variable magnitude at the point of connection. In [12], a power injection model was used to study the effect of UPFC for improving damping of oscillations with an energy function based control strategy. The power injection model is derived from the power balance equations at the UPFC network interface nodes.

Most researches have emphasized the effect of UPFCs on stability improvement and power flow control [13, 14]. In this paper the unified power flow controller is being installed in series with tie-line between any interconnected areas, which is used to stabilize the area frequency oscillations by high speed control of tie-line power through the interconnections. In addition it can also be expected that the high speed control of UPFC can be coordinated with slow speed control of governor system for enhancing stabilization of area frequency oscillations effectively. Under these situations, the governor system may no longer be able to absorb the frequency fluctuations. In order to compensate for sudden load changes, an active power source with fast response such as Redox Flow Batteries is expected as the most effective counter measure. The RFB will, in addition to load leveling, a function conventionally assigned to them, have a wide range of applications such as power quality maintenance for decentralized power supplies. The RFB are the excellent short-time overload output and the response characteristics possessed in the particular [18, 19]. The effect of generation control and the absorption of power fluctuation required for power quality maintenance are expected. However, it will be difficult to locate the placement of RFB alone in every possible area in the interconnected system due to the economical reasons. Therefore RFB coordinated with UPFC are capable of controlling the network conditions in a very fast and economical manner.

However, due to the complexity of power system such as nonlinear load characteristics and variable operating points, the integral controllers tuning with conventional methods may be unsuitable for some operating conditions. In literature, few different control strategies have been suggested based on the digital, self-tuning, adaptive, variable structure systems and intelligent/soft computing control. Recently, different Evolutionary Computation (EC) such as Differential Evolution(DE), Genetic Algorithms(GA), Simulated Annealing(SA) Particle Swarm Optimizations (PSO) , which are some of the heuristic techniques having immense 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. Amongst the population based algorithms, SA suffers from settings of algorithm parameters and gives rise to repeat revisiting of the same suboptimal solutions. The GA method is usually faster than SA method because GA has parallel search technique. Some authors have applied GA/PSO technique to optimize controller gains more effectively and efficiently than the classical approach. Recent research has brought out some deficiencies in GA/PSO performance [20, 21]. The premature convergence of GA/PSO degrades its search capability. This paper proposes a new optimization approach, to solve the LFC problem using Artificial Bee Colony (ABC) algorithm. The Artificial Bee Colony algorithm, a new swarm intelligent algorithm, was proposed by Karaboga [22] in Erciyes University of Turkey in 2005. Since ABC algorithm is simple in concept, easy to implement, and has fewer control parameters, it has been used in many fields. ABC algorithm has applied successfully to unconstrained numerical optimization problems [23].The extended version of the ABC algorithm is also developed for solving optimization problems in 2007 [24]. ABC algorithms are highly robust yet remarkably simple to implement. Thus, it is quite pertinent to apply the ABC, with more new modifications, to achieve better optimization and handle the load-frequency problems more efficiently. In this study, an ABC algorithm is used to optimizing the integral controller gains for load frequency control of a two area thermal power system considering GDB and GRC nonlinearities with UPFC and RFB. To obtain the best convergence performance, new cost function is derived by using the tie-line power and frequency deviations of the control areas and their rates of changes according to time integral. The simulation results show that the dynamic performance of the system with UPFC and RFB is improved by using the proposed controller. The organizations of this paper are as follows. In section II problem formulations are described. In section III focuses on the design and implementation of UPFC controller. The operating principles of Redox Flow Batteries are discussed in section IV. Linearized reduction model for the control design of UPFC and RFB are designed in section V. Overview of ABC algorithm is described in section VI. The output response of the system is investigated with the application of RFB unit coordinated with UPFC controllers in section VII. In Section VIII presents the simulations results and observations; finally conclusion is discussed in section IX.

## II. Problem Formulation

The state variable equation of the minimum realization model of ‘ $N$ ’ area interconnected power system may be expressed as [26].

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

Where $x = \left[x_1^T, \Delta p_{ei} \ldots\ldots x_{(N-1)}^T, \Delta p_{e(N-1)} \ldots\ldots x_N^T\right]^T$,

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*N*-*State* vector,

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

$$u = [u_1, \dots u_N]^T = \left[\Delta P_{C_1} \dots P_{C_N}\right]^T$$

*N*- Control input vector

$$d = [d_1, \dots d_N]^T = \left[\Delta P_{D_1} \dots P_{D_N}\right]^T$$

*N* - Disturbance input vector,

$$y = [y_1, \dots y_N]^T$$

2*N*- 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. In order to ensure zero steady state error condition an integral controller may suitability designed for the augmented system. To incorporate the integral function in the controller, the system (1) is augmented with new state variables defined as the integral of

$$ACE, \left(\int v_i dt\right), i = 1,2,\dots,N$$

The augmented system of the order (*N*+*n*) may be describe

$$\dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}u + \bar{\Gamma}d \qquad (2)$$

$$\bar{x} = \left[\left(\int \left[v_i\, dt\right] \; x\right)\right] (N \; n)$$

$$\bar{A} = \begin{bmatrix} 0 & C \\ 0 & A \end{bmatrix}, \bar{B} = \begin{bmatrix} 0 \\ B \end{bmatrix} \text{ and } \bar{\Gamma} = \begin{bmatrix} 0 \\ \Gamma \end{bmatrix}$$

The problem now is to design the decentralized feedback control law

$$u_i = -k_i^T \bar{y}_i \quad i = 1,2 \dots\dots, \quad N \qquad (3)$$

The control law in (3) may be written in-terms of $v_i$ as

$$u_i = -k_i \int v_i dt \quad i = 1.2 \dots\dots, \quad N \qquad (4)$$

Where $k_i$ is the integral feedback gain vector, $v_i$ is the scalar control output of area i

## III. UPFC Basic Operation And Characteristics

The UPFC unit is placed between two busses which are referred as the UPFC sending bus and the UPFC receiving bus. It consists of two Voltage-Sourced Converters (VSCs) with a common DC link. For the fundamental frequency model, the VSCs are replaced by two controlled voltage sources [15] as shown in Figure 1.The voltage source at the sending bus is connected in shunt and will therefore be called the shunt voltage source. The second source, the series voltage source, is placed between the sending and the receiving busses. The UPFC is placed on high-voltage transmission lines. This arrangement requires step-down transformers in order to allow the use of power electronics devices for the UPFC. Applying the Pulse Width Modulation (PWM) technique to the two VSCs the following equations for magnitudes of shunt and series injected voltages are obtained

$$V_{SH} = m_{SH} \frac{V_{DC}}{2\sqrt{2}\, n_{SH} V_B} \qquad (5)$$

$$V_{SE} = m_{SE} \frac{V_{DC}}{2\sqrt{2}\, n_{SE} V_B} \qquad (6)$$

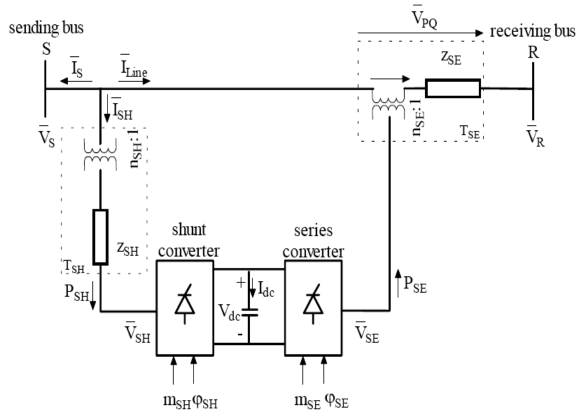


**Fig.1. Fundamental frequency model of UPFC**

Where: $m_{SH}$ – Amplitude modulation index of the shunt VSC control signal, $m_{SE}$ – Amplitude modulation index of the series VSC control signal ,$n_{SH}$ – shunt transformer turn ratio ,$n_{SE}$ – Series transformer turn ratio ,$V_B$ – The system side base voltage in kV, $V_{DC}$ – DC link voltage in kV. The phase angles of $V_{SH}$ and $V_{SE}$ are

$$\delta_{SH} = \angle(\delta_S - \varphi_{SH})$$

$$\delta_{SE} = \angle(\delta_S - \varphi_{SE}) \qquad (7)$$

Where $\varphi_{SH}$ – firing angle of the shunt VSC with respect to the phase angle of the sending bus voltage and $\varphi_{SE}$ – firing angle of the series VSC with respect to the phase angle of the sending bus Voltage. The series converter injects an AC voltage $V_{SH} = V_{SE} \angle(\delta_S - \varphi_{SE})$ in series with the transmission line. Series voltage magnitude $V_{SE}$ and its phase angle $\varphi_{SE}$ with respect to the sending bus which is controllable in the range of $0 \le V_{SE} \le V_{SE\,\max}$ and $0 \le \varphi_{SE} \le 360^0$. The shunt converter injects controllable shunt voltage such that the real component of the current in the shunt branch balance the real power demanded by the series converter. The real power can flow freely in either direction between the AC terminals. On the other hand the reactive power cannot flow through the DC link. It is absorbed or generated locally by each converter. The shunt converter operated to exchange the reactive power with the AC system provides the possibility of independent shunt compensation for the line. If the shunt injected voltage is regulated to produce a shunt reactive current component that will keep the sending bus voltage at its pre-specified value, then the shunt converter is operated in *the Automatic Voltage Control Mode.* Shunt converter can also be operated in *the Var Control Mode.* . In this case shunt reactive current is produced to meet the desired inductive or capacitive Var requirement in the UPFC is placed at the transmission line connecting buses S and R as shown in figure 2 [16]. Line conductance was neglected. UPFC is represented by two ideal voltage sources

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of controllable magnitude and phase angle. Bus S and fictitious bus S1 shown in figure 2 represent UPFC sending and receiving buses respectively.

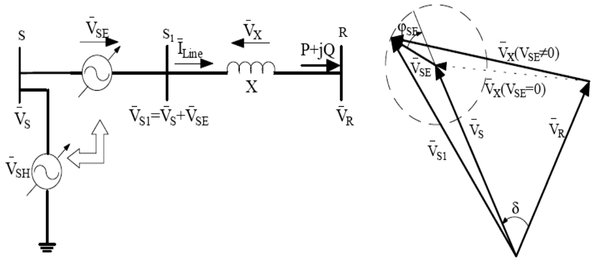

**Fig.2. Tie-line with UPFC**

In this case, the complex power received at the receiving end of the line is given by

$$S = \bar{V}_R \bar{I}_{Line}^{\ *} = \bar{V}_R \left( \frac{\bar{V}_S + \bar{V}_{SE} - \bar{V}_R}{jX} \right)^* \quad (8)$$

Where $\bar{V}_{SE} = V_{SE} \angle(\delta_S - \varphi_{SE})$

The complex conjugate of this complex power is

$$S^* = P - jQ = \bar{V}_R^{\ *} \left( \frac{\bar{V}_S + \bar{V}_{SE} - \bar{V}_R}{jX} \right) \quad (9)$$

Performing simple mathematical manipulations and separating real and imaginary components of (9) the following expressions for real and the reactive powers received at the receiving end of the line are

$$P = \frac{V_S V_R}{X} \sin\delta + \frac{V_R V_{SE}}{X} \sin(\delta - \varphi_{SE}) = P_O(\delta) + P_{SE}(\delta, \varphi_{SE})$$

$$Q = -\frac{V_R^{\ 2}}{X} + \frac{V_S V_R}{X} \cos\delta + \frac{V_R V_{SE}}{X} \cos(\delta - \varphi_{SE}) = Q_O(\delta) + Q_{SE}(\delta, \varphi_{SE}) \quad (10)$$

For $V_{SE} = 0$ the above equations represent the real and reactive powers of the uncompensated system**.** As the UPFC series voltage magnitude can be controlled between 0 and $V_{SE}$ max, and its phase angle can be controlled between 0 and 360 degrees at any power angle δ, and using (10) the real and reactive power received at bus R for the system with the UPFC installed can be controlled between

$$P_{\min}(\delta) \le P \le P_{\max}(\delta)$$

$$Q_{\min}(\delta) \le Q \le Q_{\max}(\delta) \quad (11)$$

Where

$$P_{\min}(\delta) = P_0(\delta) - \frac{V_R V_{SE\max}}{X}$$

$$P_{\max}(\delta) = P_0(\delta) + \frac{V_R V_{SE\max}}{X}$$

$$Q_{\min}(\delta) = Q_0(\delta) - \frac{V_R V_{SE\max}}{X}$$

$$Q_{\max}(\delta) = Q_0(\delta) + \frac{V_R V_{SE\max}}{X}$$

Rotation of the series injected voltage phasor with RMS value of $V_{SE\max}$ from 0 to $360^0$ allows the real and the reactive power flow to be controlled within the boundary.

## IV. OPERATING PRINCIPLE OF REDOX FLOW BATTERIES

The configuration of Redox Flow Battery is shown in figure 3. A sulfuric acid solution containing vanadium ions is used as the positive and negative electrolytes, which are stored in respective tanks and circulated to battery cell. The reactions that occur in the battery cell during charging and discharging can be expressed simply with the following equations [18]

$$\text{Positive Electrode} : V^{4+} \underset{discharge}{\overset{charge}{\rightleftarrows}} V^{5+} + e^- \quad (12)$$

$$\text{Negative Electrode} : V^{3+} + e^{-} \underset{discharge}{\overset{charge}{\rightleftarrows}} V^{2+} \quad (13)$$

The Redox Flow Batteries offer the following features, and are suitable for high capacity systems that differ from conventional power storage batteries. The battery reaction only involves a change in the valence of a vanadium ion in the electrolyte. There are none of the factors which reduce the battery service life seen in other batteries that use a solid active substance, such as loss are electro depositions of the active substance.

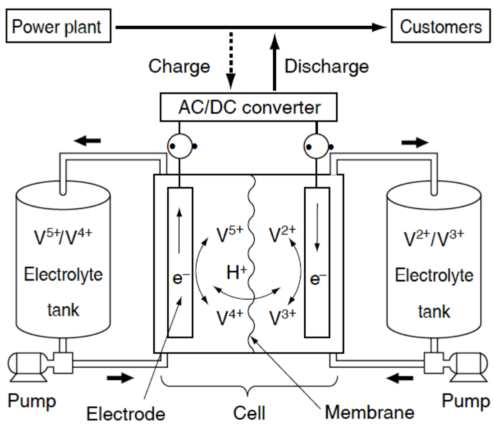


**Fig.3. Principles of a Redox Flow Battery**

Furthermore, operations at normal temperatures ensure less deterioration of the battery materials due to temperature. Pumps and piping that are widely used in facilities such as chemical plants are usable as established technologies. The system configurations are such that battery output (cell section) and battery capacity (tank section) can be separated, therefore the layout of the sections can be altered according to the place of installation. For example, the tank can be placed underground. The design can be easily modified according to the required output and capacity. The charged electrolyte is stored in separate positive and negative tanks when the battery has been charged, therefore no self-discharge occurs during prolonged stoppage nor is auxiliary power required during stoppage. Furthermore, start-up after prolonged stoppage requires only starting of the pump, thus making start-up possible in only a few minutes. The electrolyte (i.e., the active substance) is sent to the each battery cell from the same tank, therefore the charging state of each battery cell is the same, eliminating the need for

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special operation such as uniform charging. so that, maintenance is also easy because the electrolyte is relatively safe and the operating are at normal temperature and assures superior environmental safety. Waste vanadium from generating stations can be used so it can be superior recyclability. Furthermore, the vanadium in the electrolyte can be used semi-permanently.

The RFB systems are incorporated in the power system to suppress the load frequency control problem and to ensure an improved power quality. In particular, these are essential for reusable energy generation units, such as wind power and photovoltaic generator units, which need measures for absorption of changes in output and to control flicker and momentary voltage drop. With the excellent short-time overload output and response characteristics possessed by RFB in particular [19], the effects of generation control and of the absorption of power fluctuation needed for power quality maintenance are expected. The set value of the RFB has to be restored at the earliest, after a load disturbance so that the RFB unit is ready to act for the next load disturbance. The RFB are capable of very fast response and therefore, hunting due to a delay in response does not occur. For this reason, the ΔFi was used directly as the command value for LFC to control the output of RFB as shown in Figure 4.

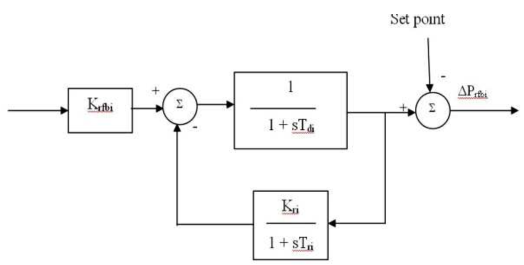


**Fig.4. Redox Flow Battery System Models**

## V. SYSTEM MODELING FOR CONTROL DESIGN

The RFB and UPFC are found to be superior to the governor system in terms of the response speed against, the frequency fluctuations. Therefore, the operational tasks are assigned according to the response speed as follow. The RFB and UPFC are charged with suppressing the peak value of frequency deviations quickly against the sudden load change, subsequently the governor system are charged with compensating for the steady state error of the frequency deviations. Figure 5 shows the model for the control design of RFB and UPFC. Where the dynamics of governor systems are eliminated by setting the mechanical inputs to be constant since the response of governor is much slower than that of RFB or UPFC. The RFB is modeled as an active power source to area 1.with a time constant $T_{RFB}$. The UPFC is modeled as a tie line power flow controller with a time constant $T_{SSSC}$. The tie-line power modulated by the UPFC flows into both areas simultaneously with different signs (+ and -) since the responses of power control by the RFB and by the UPFC are sufficiently fast compared to the dynamics of the frequency deviations, the time constants $T_{RFB}$ and $T_{UPFC}$ are regarded as 0 sec for the control design. Then the state equation of the system represented by figure 5 becomes.

$$\begin{bmatrix}\Delta\dot{F}_1\\ \Delta\dot{P}_{T12}\\ \Delta\dot{F}_2\end{bmatrix}=\begin{bmatrix}-\frac{1}{T_{p1}} & -\frac{k_{p1}}{T_{p1}} & 0\\ 2\pi T_{12} & 0 & -2\pi T_{12}\\ 0 & \frac{a_{12}k_{p2}}{T_{p2}} & -\frac{1}{T_{p2}}\end{bmatrix}\begin{bmatrix}\Delta F_1\\ \Delta P_{T12}\\ \Delta F_2\end{bmatrix}+\begin{bmatrix}\frac{k_{p1}}{T_{p1}} & -\frac{k_{p1}}{T_{p1}}\\ 0 & 0\\ 0 & \frac{a_{12}k_{p2}}{T_{p2}}\end{bmatrix}\begin{bmatrix}\Delta P_{RFB}\\ \Delta P_{UPFC}\end{bmatrix} \quad (14)$$

Here, from the physical view point it is noted that the UPFC located between two areas is effective to stabilize the inter-area oscillation mode only, and then the RFB which is capable of supplying the energy into the power system should be suitable for the control of the inertia mode.

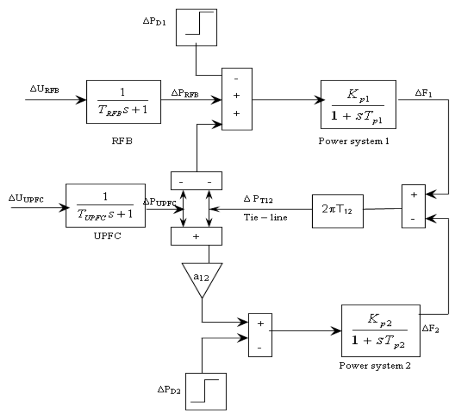


**Fig.5. Linearized reduction model for the control design**

### *A. Control design of RFB*

The design process starts from the reduction of two area system into one area which represents the Inertia centre mode of the overall system. The controller of RFB is designed in the equivalent one area system to reduce the frequency deviation of inertia centre. The equivalent system is derived by assuming the synchronizing coefficient $T_{12}$ to be large. From the state equation of $\Delta\dot{P}_{T12}$ in (14)

$$\frac{\Delta\dot{P}_{T12}}{2\pi T_{12}}=\Delta F_1-\Delta F_2 \quad (15)$$

Setting the value of $T_{12}$ in (15) to be infinity yields $\Delta F_1 = \Delta F_2$. Next, by multiplying state equation of $\Delta\dot{F}_1$ *and* $\Delta\dot{F}_2$ in (14) by $\frac{T_{p1}}{k_{p1}}$ and $\frac{T_{p2}}{a_{12}k_{p2}}$ respectively, then

$$\frac{T_{p1}}{k_{p1}}\Delta\dot{F}_1=-\frac{1}{k_{p1}}\Delta F_1-\Delta P_{T12}-\Delta P_{UPFC}+\Delta P_{RFB} \quad (16)$$

$$\frac{T_{p2}}{a_{12}k_{p2}}\Delta\dot{F}_2=\frac{-1}{kp_2\,a_{12}}\Delta F_2+\Delta P_{T12}+\Delta P_{UPFC} \quad (17)$$

By summing (16) and (17) and using the above relation $\Delta F_1 = \Delta F_2 = \Delta F$

$$\Delta\dot{F}=\frac{\left(-\frac{1}{k_{p1}}-\frac{1}{k_{p2}a_{12}}\right)}{\left(\frac{T_{p1}}{k_{p1}}+\frac{T_{p2}}{k_{p2}a_{12}}\right)}\Delta F+\frac{1}{\left(\frac{T_{p1}}{k_{p1}}+\frac{T_{p2}}{k_{p2}a_{12}}\right)}\Delta P_{RFB}+C\Delta P_D \quad (18)$$

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Where the load change in this system $\Delta P_D$ is additionally considered, here the control $\Delta P_{RFB} = -K_{RFB}\ \Delta F$ is applied then.

$$\Delta F = \frac{C}{S + A + K_{RFB}\ B} \Delta P_D \quad (19)$$

Where

$$A = \left( -\frac{1}{k_{p1}} - \frac{1}{k_{p2} a_{12}} \right) \Big/ \left( \frac{T_{p1}}{k_{p1}} + \frac{T_{p2}}{k_{p2} a_{12}} \right)$$

$$B = \frac{1}{\left[ \frac{T_{p1}}{K_{p1}} + \frac{T_{p2}}{K_{p2} a_{12}} \right]}$$

Since the control purpose of RFB is to suppress the deviation of $\Delta F$ quickly against the sudden change of $\Delta P_D$, the percent reduction of the final value after applying a step change $\Delta P_D$ can be given as a control specification. In (19) the final values with $K_{RFB} = 0$ and with $K_{RFB} \neq 0$ are C/A and C/(A+$K_{RFB}$ B) respectively therefore the percent reduction is represented by

$$C/(A + K_{RFB}\ B) \big/ (C / A) = R/100 \quad (20)$$

For a given value of speed regulation coefficient- R, the control gain of RFB is calculated as

$$K_{RFB} = \frac{A}{BR}(100 - R) \quad (21)$$

### B. *Control Design of UPFC*

The active power controller of UPFC has a structure of the Lead-Lag compensator with output signal $\Delta P_{ref.}$ In this study the dynamic characteristics of UPFC is modeled as the first order controller with time constant $T_{UPFC}$ . It is to be noted that the injected power deviations of UPFC, $\Delta P_{UPFC}$ acting positively on the area1 reacts negatively on the area2. Therefore $\Delta P_{UPFC}$ flow into both area with different signs (+,-) simultaneously. The commonly used Lead-Lag structure is chosen in this study as UPFC based supplementary damping controller as shown in figure 6. The structures consist of a gain block. A signal washout block and Two-stage phase compensation block. The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and output signals. The signals associated with oscillations in input signal to pass unchanged without it steady changes in input would modify the output the input signal of the proposed UPFC-based controller is frequency deviation $\Delta f$ and the output is the change in control vector $\Delta P_{UPFC}$ . From the view point of the washout function the value of washout time constant is not critical in Lead-Lag structured controllers and may be in the range 1 to 20seconds. The controller gain K; and the time constant $T_1$, $T_2$, $T_3$ and $T_4$ are optimized with the objective function (27) using ABC algorithm

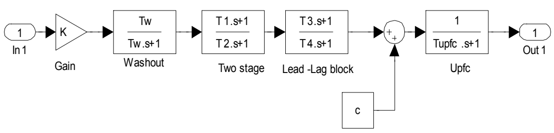


**Fig.6. Structure of UPFC-based damping controller**

## VI. Artificial Bee Colony [ABC] Algorithm

The Artificial Bee Colony [ABC] algorithm which was introduced in 2005 by Karaboga mimics the food foraging behavior of swarms of honey bees. Honey bees use several mechanisms like waggle dance to optimally locate food sources and to search new ones. This makes them a good candidate for developing new intelligent search algorithms. It is very simple, robust and population based stochastic optimization algorithm. In ABC algorithm, the colony of artificial bees consists of three groups of bees: employed bees, onlookers and scout bees. Some of the bee of the colony consists of the employed artificial bees and the some includes the onlookers. For every food source, there is only one employed bee. In other works, the number of employed bees is equal to the number of food sources around the hive. The employed bee whose the food sources has been abandoned by the bees becomes a scout. In ABC algorithm the position of the food sources determines the solution and the amount of nectar represents to fitness of this respective solution. The foraging strategy is governed by three process namely initialization, Reproduction and Replacement of bee and selection [23].

a. Initialization

A randomly distributed initial populations solutions *[$X_i$=1, 2, 3…D]* is being dispread over the *D* dimensional problem space.

b. Reproduction

An artificial onlooker bee choose a food source depending on the probability value associated with that food source, *Pi*, calculated by the following expression,

$$Pi = \frac{f_i * t_i}{\sum_{n=1}^{N} f_i * t_i} \quad (22)$$

Where s the fitness values of the solution *i* which is proportional to the nectar amount of the food source in the position *i* and *N* is the number of food sources which is equal to the number of employed bees. In order to produce a candidate food position from the old one in memory, the ABC uses the following expression.

$$V_{ij} = x_{ij} + \varphi_{ij}\left(x_{ij} - x_{kj}\right) \quad (23)$$

Where *k = (1,2,3….D)* and *j =( 1,2,3...N)* are randomly chosen indexes $\Psi$ $\varphi_{ij}$ is a random number between [-1,1].

c. Replacement of Bee selection

In ABC, providing that a position cannot be improved further through a predetermined number of cycles, then that food source is assumed to be abandoned. The value of pre determined number of cycles is an important control parameter of the ABC algorithm, which is called "limit" for abandonment .Assume that the abandoned source is $X_i$ and *J=(1,2,3,….N)*,then the scout discovers a new food source to be replaced with $X_i$. This operation can be defined as

$$X_i^j = X_{\min}^j + rand\ (0,1) * \left(X_{\max}^j - X_{\min}^j\right) \quad (24)$$

After each candidate source position $V_{ij}$ , is produced and then evaluated by the artificial bee ,its performance is

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compared with that of its old one. If the new food has equal or better nectar than the old source, it replaces the old one in the memory. Otherwise, the old one is retained in the memory.

### *A. ABC algorithm implemented in the LFC*

The following algorithm is adopted for the proposed ABC algorithm for LFC problem.

1. Initialize the food source position $x_i$ (solutions population) where *i=12 ….D*
2. Calculate the nectar amount of the population by means of their fitness values using:
   $f_i *t_i=1/(1+obj.fun._i J)$
   Where *obj.fun.*$_i$ represents of equation at solution *i* (27)
3. Produce neighbor solution $V_{ij}$ for the employed bees by using equation (23) and evaluate them as indicated in step2.
4. Apply the greedy selection process for the employed bees.
5. If all onlooker bees are distributed, Go to step 9 Other-wise, Go to the next step.
6. Calculate the probability values $P_i$ for the solution $X_i$ using by equation (22).
7. Produce the neighbor solution $V_i$ for the onlookers bee from the solution $X_i$ selected depending on $P_i$ and evaluate them
8. Apply the greedy selection process for the onlooker bees.
9. Determine the abandoned solution for the scout bees, if it exists, and replace it with a completely new solution $X_i^j$ using equation (24) and evaluate them as indicated in step2.
10. Memorize the best solution attained so for.
11. If cycle=Maximum Cycle Number(MCN). Stop and print result, otherwise follow step 3.

The employed and Onlooker bees select new food sources in the neighborhood of the previous one in their memory depending on visual information. Visual information is based on the comparison of food –source positions. On the other hand, Scout bees, without any guidance while looking for a food-source position, explore a completely new food-source position. Therefore Scouts bees are characterized based on their behavior by low search costs and a low average in food-source quality. Occasionally, the Scouts bee can be fortunate to discover rich, entirely unknown food sources. In the case of artificial bee, the artificial Scouts bee could have the fast discovery of the group of feasible solutions as the task [24]. Parameter tuning in meta-heuristic optimization algorithms influences the performances of the algorithm significantly. Divergence, becoming trapped in local extreme and time consumption are such consequences of setting the parameter improperly. The ABC algorithm as an advantage has a few controlled parameters, since initializing populations “randomly” with a feasible region is sometimes cumbersome. The ABC algorithm does not depend on the initial population to be in a feasible region. Instead, its performance directs the population to the feasible region sufficiently [25].

## VII. SYSTEM INVESTIGATED

The aim of load frequency control is that the steady state errors of the frequency and tie-line power deviations following a step load change should approach zero. For this purpose, to obtain the appropriated control inputs, Integral controllers are used together with area control errors, $ACE_1$ and $ACE_2$.

$$ACE_1 = \beta_1 \Delta f_1 + \Delta p_{tie1}$$
$$ACE_2 = \beta_2 \Delta f_2 + \Delta p_{tie2} \qquad (25)$$

The control inputs of the power system, $u_1$ and $u_2$ are obtained and adopted with the Integral controllers as shown below.

$$u_1 = K_{i1} \int ACE_1 \, dt$$
$$u_2 = K_{i2} \int ACE_2 \, dt \qquad (26)$$

Investigations have been carried out in the two equal area interconnected thermal power system and each area consists of two reheat units with GDB and GRC nonlinearities as shown in figure 8. The nominal parameters are given in Appendix. $apf_{11}$ and $apf_{12}$ are the area participation factors in area 1 and $apf_{21}$ and $apf_{22}$ are the area participation factor in area2. Note that $apf_{11}+apf_{12} = 1.0$ and $apf_{21}+apf_{22} = 1.0$. In this study the active power model of UPFC controllers is fitted in the tie-line near area1 to examine its effect on the power system performance. Then RFB unit installed in area1 and coordinated with UPFC controller for LFC to study its performance of system. The following object of obtaining the optimal solutions of control inputs is taken an optimization problem, and the novel cost function [27] in (27) are derived by using the frequency deviations of control areas and tie line power changes and their rates of changes. The integral controller gain is tuned with ABC algorithm by optimizing the solutions of control inputs. The simulations are realized for a step load perturbation of 1% in area1. The results are obtained by MATLAB 7.01 software are used and 50 iterations are chosen for converging to solution in the ABC algorithm.

$$J = \int_0^T \{(\beta_1 \Delta f_1)^2 + (\beta_2 \Delta f_2)^2 + (\Delta P_{tie12})^2\} \qquad (27)$$

### *A. Governor Dead Band (GDB) nonlinearity*

Governor dead band is defined as total magnitude of a sustained speed change within which there is no resulting change in valve position. The backlash non-linearity tends to produce a continuous sinusoidal oscillation with a natural period of about 2s [3]. The speed governor dead band has significant effect on the dynamic performance of load frequency control mechanism. In this study, describing function approach is used to incorporate the governor dead band non-linearity. The hysteresis types of non-linearity are expresses as

$$y = F(x, \dot{x}) \quad \text{Rather than as} \quad y = F(x) \qquad (28)$$

To solve the non-linear problem, it is necessary to make the assumption that the variable x, appearing in (28) is sufficiently close to a sinusoidal equation (29) that is

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$$x = A \sin w_o t \quad (29)$$

Where; $A$= Amplitude of oscillation, $w_o$ = Frequency of oscillation $w_o = 2\pi f_o = \pi$ (30)

As the variable function is complex and periodic function of time, it can be developed in a Fourier series as [3]

$$F(x, \overset{*}{x}) = F^o + N_1 x + \frac{N_2}{w_o}\overset{*}{x} + ......... \quad (31)$$

As the back lash nonlinearity is symmetrical about the origin, $F^o$ is zero. For the analysis, in this study, back lash nonlinearity of about 0.05% for thermal system is considered. In (31), neglect higher order, the Fourier co-efficient are derived as $N_1 = 0.8$ and $N_2 = -0.2$. By substituting the $N_1$ and $N_2$ values in (31), the transfer function model of governor dead band non-linearity is expressed as

$$F(x, \overset{*}{x}) = 0.8x - \frac{0.2}{\pi}\overset{*}{x} \quad (32)$$

### *B. Generation Rate Constraint (GRC) nonlinearity*

In most of the LFC studies, the effect of Generation Rate Constraint (GRC) nonlinearity is neglected for simplicity. But for a realistic analysis of the performance of the system, this should be included as it has a considerable effect on the amplitude and settling time of the oscillations [3]. It is a known fact that the steam power plants used for power generation can change only at a specified maximum rate. The generation rate (from safety consideration of the equipment) for reheat units is quite low. Most of the reheat units have a generation rate around 3% per min. some have a generation rate between 5 to 10% per min [4]. If these constraints are not considered, system is likely to chase large momentary disturbances. When GRC is considered, the system dynamic model becomes nonlinear and linear control techniques cannot be applied for the optimization of the controller setting. Instead of augmenting the generation rates $Pg_i$ while solving the state equations, it may be verified at each step, if the $GRC_s$ are violated. Another way of considering $GRC_s$ for both areas is to add limiters to the governors as shown in figure 7, the maximum rate of valve opening or closing speed is restricted by the limiters. The banded values imposed by the limiters are selected to restrict the generation rate by 10% per min. In establishing LFC signals, it should be recognized that there is a limit to the rate at which generating unit outputs can be changed. This is particularly true for thermal units where mechanical and thermal stresses are limiting factors. In this study a generation rate constraint of 0.0017 p.u.MW $sec^{-1}$ is considered for thermal system, i.e.

$$\Delta \overset{*}{P_g} \leq 0.1 p.u.MW \min^{-1} = 0.0017\, p.u.MW \sec^{-1} \quad (33)$$

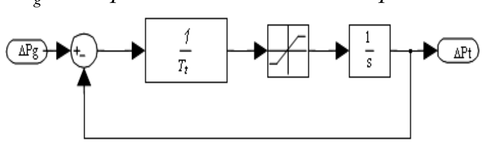


**Fig.7. Nonlinear Turbine Model with GRC**

## VIII. SIMULATIONS RESULT AND OBSERVATIONS

The optimal gains of Integral controllers ($K_{I1}$ $K_{I2}$) for three case studies are determined using ABC algorithm. At the end of the simulation, the tuned parameters of the control system are shown in Table I. These controllers are implemented in two-area interconnected reheat thermal power system considering nonlinearities without UPFC and RFB, with UPFC only, UPFC coordinated RFB. The optimal gain and time constant of UPFC based damping controller are found using ABC algorithm as K = 0.69; $T_1$ = 0.4523; $T_2$ = 0.5916; $T_3$ = 0.71085; $T_4$ = 0.2478. Figure 9 shows dynamic responses area frequencies and tie-line power deviations and figure 10 shows the dynamic responses of the Control input deviations for 1 % step load disturbance in area1 considering area participation factors $apf_{11} = apf_{12} = 0.5$ and $apf_{21} = apf_{22} = 0.5$. It can be observed that the oscillations in area frequencies and tie-line power deviations have decreased to a considerable extent as compared to that of the system without UPFC controllers. Moreover the RFB located in area 1which as coordinated with UPFC controllers, the gain of RFB $K$rfbi = 0.65 are calculated using (21) for given value of speed regulation coefficient(R) as shown in appendix. Redox Flow Batteries have improving the inertia mode oscillation. It is seen from figures 9 and 10; it is evident that the dynamic responses have improved significantly with the use of UPFC units when connected with the tie-line and coordinated with RFB. The settling times and peak over/under shoot for the frequency deviations in each area and tie-line power deviations for three case studies are tabulated in Table II. As the load disturbance has occurred in area1, at steady state, the powers generated by generating units in area1 are in proportion to the area participation factors. Therefore, as in figure 11, at steady state $\Delta Pg_{1ss} = \Delta Pg_{2ss} = \Delta PD_1 * apf_{11} = 0.01*0.5 = 0.005$ p.u.Mw and similarly, $\Delta Pg_{3ss} = \Delta Pg_{4ss} = \Delta PD_2 * apf_{21} = 0 * 0.5 = 0$ p.u.Mw. From the Table I and II, it can be found that the controller designed using ABC algorithm for two area thermal reheat thermal power system with UPFC coordinated with RFB have not only reduces the cost function but also ensure better stability, as they possesses less over/under shoot and faster settling time when compared with the output response of the system used without UPFC and RFB units. Moreover the RFB units, suppresses the peak frequency deviations of both areas, and continue to eliminate the steady state error of frequency deviations as expected.

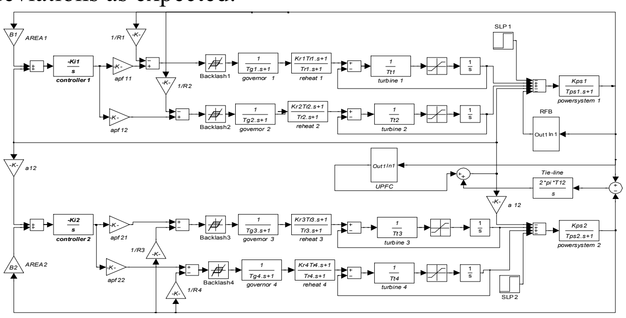

**Fig.8. Transfer Function model of two-area interconnected thermal reheat power system considering GDB and GRC nonlinearities with UPFC and RFB**

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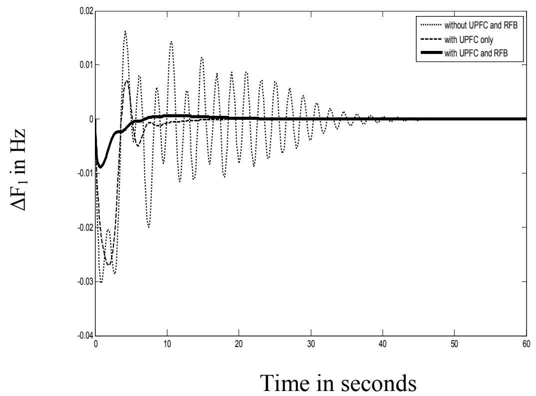
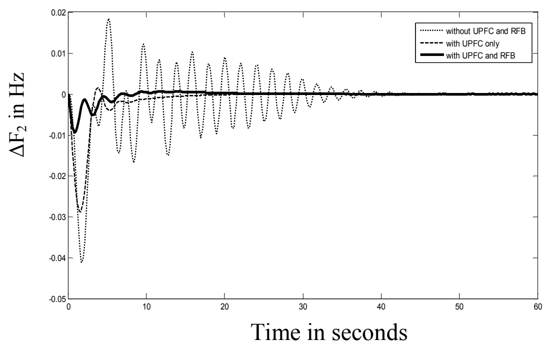
**TABLE I: Tuned Parameter of the Control System for Three Case Studies**

| Two area interconnected power system considering nonlinearities | Feedback gain($K_i$) | Cost function value [J] |
|---|---|---|
| **Case:1** without UPFC and RFB units | 0.1731 | 0.7246 |
| **Case:2** with UPFC unit only | 0.2015 | 0.2995 |
| **Case:3** with UPFC and RFB units | 1.0691 | 0.0246 |



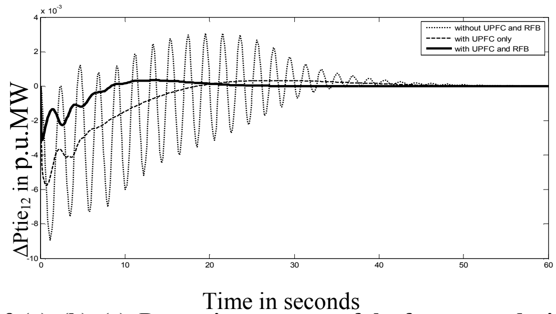
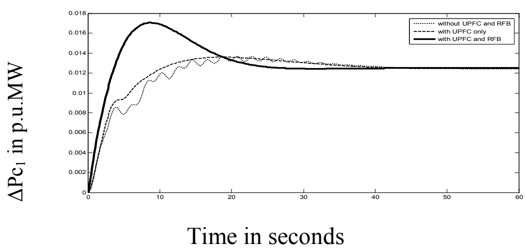




**Fig.9 (a), (b), (c). Dynamic responses of the frequency deviations and tie line power deviation considering a step load disturbance of 0.01p.u.Mw in area1**



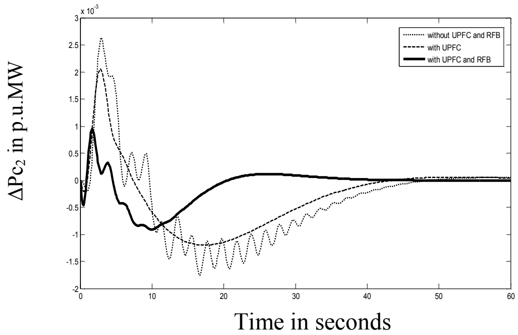
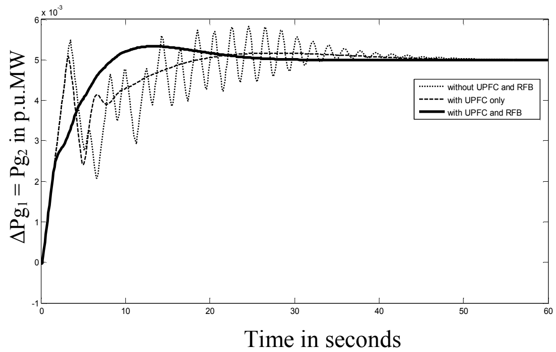




**Fig.10 (a),(b) . Dynamic responses of the Control input deviations considering step load disturbance of 0.01p.u.Mw iarea1.**



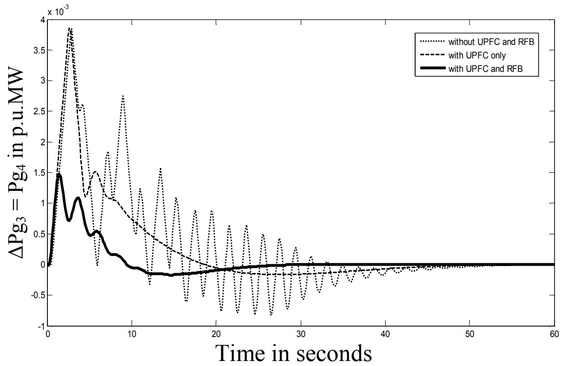




**Fig.11 (a), (b). Dynamic responses of the required additional mechanical power generation for step load disturbance of 0.01 p .u .Mw in area 1**

**TABLE II : Comparison of the System Performance for the Three Case Studies**

| Two area interconnected power system considering nonlinearities | Setting time ( $\tau_s$ ) in seconds | | | Peak over / under shoot | | |
|---|---|---|---|---|---|---|
| | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie}$ | $\Delta F_1$ in Hz | $\Delta F_2$ in Hz | $\Delta P_{tie}$ p.u. MW |
| **Case:1** without UPFC and RFB units | 42.35 | 40.44 | 47.14 | 0.0303 | 0.0405 | 0.0089 |
| **Case:2** with UPFC unit only | 14.13 | 12.53 | 28.13 | 0.0267 | 0.0285 | 0.0057 |
| **Case:3** with UPFC and RFB units | 9.61 | 8.78 | 19.32 | 0.0087 | 0.0091 | 0.0033 |

## IX. CONCLUSION

In this paper, a sophisticated Load Frequency Control by Redox Flow Batteries co-ordinate with UPFC controller has been proposed for a two area interconnected Reheat Thermal Power System considering GDB and GRC nonlinearities. The ABC algorithm is easy to implement without additional computational complexity to achieve the optimal parameters. This algorithm has superior solution quality in satiating the objective. This capability of ABC rises from the greedy selection process and the timely abandonment of used up food sources incorporated in it. These fundamental procedures in the ABC prevent stalling of solution and make the algorithm more exploitative in nature. A control strategy has been proposed to adjust the of the series voltage or shunt current of UPFC which in turn controls the inter-area tie- line power flow. Moreover, for an overload condition for a short time period because of nature of RFB the extremely faster response is obtained. The RFB unit has a reduced charging and discharging period. From this it is evident that RFB contributes a lot in promoting the efficiency of overall generation control through the effect of the use in load leveling and the assurance of LFC capacity after overload characteristic and quick responsiveness. Simulation results reveal that the design concept of damping the inertia mode and inter-area mode, the co-ordinate control is effective to suppress the frequency deviation of both areas and tie-line power oscillations. It may be therefore be concluded that, the Redox Flow Batteries 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 UPFC be expected to be utilized as a new ancillary service for stabilization tie-line power oscillations in the congestion management environment of the power system.

## APPENDIX

(A) Data for Thermal Reheat Power System [26]

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 sec, $T_{r1} = T_{r2} = T_{r1} = T_{r2}$ = 10 sec, $T_{t1} = T_{t2} = T_{t3} = T_{t4}$ = 0.3 sec, $K_{p1} = K_{p2}$ = 120Hz/p.u.MW, $T_{p1} = T_{p2}$ = 20 sec, $\beta_1 = \beta_2$ = 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, $\Delta P_{D1}$ = 0.01 p.u.MW.

(B) Data for UPFC [17] $T_{UPFC}$=0.01 sec; $T_w$=10 sec.

(C) Data for RFB [19] $Kri = 0$, $T_{di} = 0$, $T_{ri} = 0$

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