OPEN ACCESS INTERNATIONAL JOURNAL OF SCIENCE & ENGINEERING

DIFFERENTIAL EVOLUTION ALGORITHM BASED LOAD FREQUENCY CONTROL FOR INTERCONNECTED POWER SYSTEMS CONSIDERING NON-LINEARITIES WITH RFB AND UPFC

B. Paramasivam

Assistant Professor, Department of Electrical Engineering, Annamalai University, Annamalainagar, Tamilnadu, India.

Abstract: **This paper presents Load Frequency Control (LFC) of a two-area thermal reheat power system considering Governor Dead-Band (GDB) and Generation Rate Constraints (GRC) nonlinearities. A new Proportional-Double Integral (PI2) controller is design and implemented in LFC loop. The proposed controller have two integrators can able to reduce the area control error to zero even the system has complexities. The control parameters of the proposed controller are optimized using Differential Evolution (DE) algorithm. The main merits PI2 controller is that it has good stability during load variations, excellent transient and dynamic responses Moreover this paper deals with the concept of LFC in two-area interconnected power system having coordinated control action with Redox Flow Battery (RFB) unit places in area1 and Unified Power Flow Controller (UPFC) unit in series with the tie-line are capable of controlling the network performance in a very fast manner and improve power transfer limits**

Keywords*: Differential Evolution algorithm, Proportional-Double Integral (PI2) controller, Redox Flow Battery and Thyristor Controlled Phase Shifter.*

∴ ∴ ∴

I INTRODUCTION

The successful operation of interconnected power systems requires the matching of total generation with total load demand and associated system losses. The operating point of a power system changes with time and hence systems may experience deviations in nominal system frequency and scheduled power exchanges to other area, which may yield undesirable effects [1]. The frequency and the interchanged power are kept at their desired values using feedback for the integral of the Area Control Error (ACE), containing the frequency deviation and the error of the tie-line power, and controlling the prime movers of the generators. The controllers so designed regulate the ACE to zero [2]. The conventional control strategy for the LFC problem is to take the integral of the ACE as the control signal. An integral controller provides zero steady state deviation, but it exhibits poor dynamic performance. Among the various types of load-frequency controllers, the most widely employed is the 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. The PI controller is very simple for implementation and gives a better dynamic response, but their performances deteriorate when the complexity in the system increases due to disturbances [3, 4]. PI controller produces steady-state offset for a ramp signal similarly to the way a proportional controller does for a step change. Even though PI controllers have wide usages in controlling the Load Frequency Control (LFC) problems the Integral gain in PI controller is limited relatively to small values because of its high the overshoot in the transient's response. So that a new control strategy, a controller with two integrators such as the Proportional plus Double Integral (PI^2) is required to reduce this error to zero was proposed and adopted in this paper. The two integral time-constants values of the PI^2 controller which cause repeated roots in the controller transfer function, minimizing any adverse impact on the closed-loop stability. A lot of work pertaining to classical controllers for a power system has been carried-out. However, in most of the cases, the mathematical has been over simplified by ignoring the simultaneous presence of important system nonlinearities such as GDB and Generation Rate Constraints GRC. The Governor Dead Band is defined as the total magnitude of a sustained speed change within which there is no change in valve position. The GDB nonlinearities tend to produce unexpected sustaining oscillations in area frequency and tie-line power transient response [5]. In establishing LFC signals, it should recognize that there is a limit to the rate at which generating unit output can be changed. This is particularly true for thermal units where mechanical and thermal stresses are the limiting factors. The GRC of the system is considered by adding limiter to the control system [6].

The Unified Power Flow Controller (UPFC) is also a member of the FACTS family with very attractive features which are able to control, simultaneously or selectively, all the parameters (voltage, impedance and phase angle) affecting power flow in the transmission line [7]. 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 / active power flow control in addition to UPFC bus voltage /shunt reactive power control. The shunt 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 / active power flows by injecting a series voltage of adjustable magnitude and phase angle [8]. The main reason is the non-availability of required power other than the stored energy in the generator rotors, which can improve the performance of the system, in spite of sudden increased load demands. In order to compensate for sudden load changes, an active power source with fast response such as Redox Flow Batteries (RFB) has a wide range of applications such as power quality maintenance of decentralized power supplies. The RFB has effectively short-time overload output and have efficient response characteristics in the particular [9, 10].

Differential Evolution (DE) algorithm employs a greedy selection process with inherent elitist features. Also it has a minimum number of EA control parameters, which can be tuned effectively [11, 12]. In view of the above, an attempt has been made in this paper for the optimal design of DE based PI^2 controller for LFC in two area interconnected power system considering GDB and GRC non-linearity. The design problem of the proposed controller is formulated as an optimization problem and DE is employed to search for optimal controller parameters. By minimizing the proposed objective functions, in which the deviations in the frequency and tie line power and settling times are involved; dynamic performance of the system is improved. Simulation results are presented to show the effectiveness of the proposed controller in providing good damping characteristic to system oscillations over a wide range of loading conditions, disturbance and system parameters. In the study DE algorithm based PI^2 for LFC loop for two-area interconnected power system considering GDB and GRC nonlinearities with RFB and UPFC is considered.

II APPLICATION OF RFB AND UPFC UNIT IN A TWO- AREA POWER SYSTEM

2.1 Mathematical Modeling of Redox Flow Batteries unit

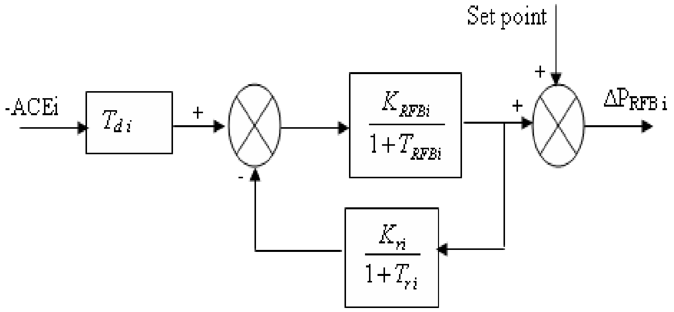

Figure 1: Redox Flow Battery System model

Electrochemical flow cell systems, also known as Redox flow batteries, convert electrical energy into chemical potential energy by means of a reversible electrochemical reaction between two liquid electrolyte solutions. In contrast with conventional batteries, Redox flow cells store energy in the electrolyte solutions. Therefore, the power and energy ratings are independent, with the storage capacity determined by the quantity of electrolyte used and the power rating determined by the active area of the cell stack. The Redox Flow Batteries (RFB) are incorporated in the power system to meet the load frequency control problems and to ensure an improved power quality. In particular, these are essential for load levelling like wind power and photovoltaic generating units, which need measures for absorption of changes in output and to control flicker and momentary voltage drop. The Redox Flow Batteries are capable of ensuring a very fast response and therefore, hunting due to a delay in response does not occur.

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, the effects of generation control and of the absorption of power fluctuation needed for power quality maintenance are expected. The Redox Flow Batteries are capable of ensuring a very fast response and therefore, hunting due to a delay in response does not occur. For this reason, the ACE$_i$ was used directly as the command value for LFC to control the output of RFB. The block diagram representation of RFB unit is shown in Fig 1. The Area Control Error (ACE) can be used as the control signal to the RFB unit.

2.2 Mathematical Modelling of UPFC unit

The UPFC unit is an effective FACTS device which is placed between two busses 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 as shown in Fig 2 [7, 8]. 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

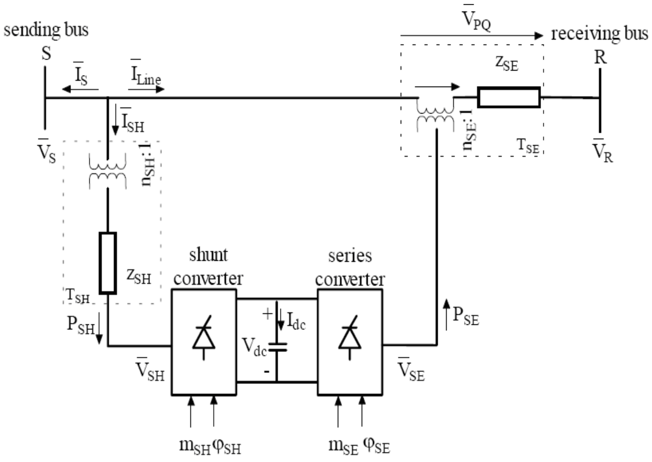

Figure 2: Fundamental frequency model of UPFC

$$V_{SH} = m_{SH}\frac{V_{DC}}{2\sqrt{2}n_{SH}V_B} \quad (1)$$

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

Where: m_{SH} – Amplitude modulation index of the shunt VSC control signa, 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

$$\delta_{SH} = \angle(\delta_S - \varphi_{SH}) \quad (3)$$

$$\delta_{SE} = \angle(\delta_S - \varphi_{SE}) \quad (4)$$

Where φ_{SH} is the firing angle of the shunt VSC with respect to the phase angle of the sending bus voltage, φ_{SE} is the firing angle of the series VSC with respect to the phase angle of the sending end 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 φ_{SE} with respect to the sending bus which is controllable in the range of 0≤ $V_{SE} \le V_{SE\max}$ and 0≤ $\varphi_{SE} \le 360^0$. 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 as the reactive power cannot flow through the DC link, it is being 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 end 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. UPFC is placed in the transmission line between buses S and R as shown in Fig 3. Line conductance was neglected. UPFC unit is represented by two ideal voltage sources of controllable magnitude and phase angle. Bus S and fictitious bus S_1 are shown in Fig 2 which represents UPFC' s sending and receiving buses respectively. In this case, the complex power received at the receiving end of the line is given by

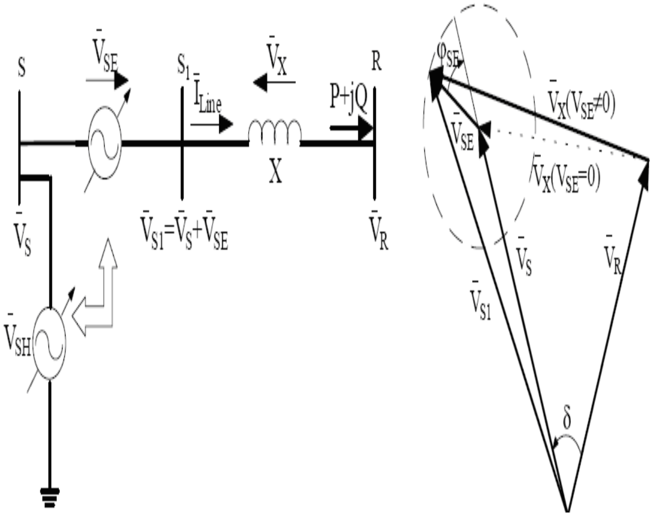

Figure 3: Application of UPFC in the tie-line

$$S=\overline{V_R}\,\overline{I_{Line}}^{*}=\overline{V}_R\left(\frac{\overline{V}_S+\overline{V}_{SE}-\overline{V}_R}{jX}\right)^{*} \qquad (5)$$

Where $\overline{V_{SE}}=V_{SE}\angle\left(\delta_S-\varphi_{SE}\right)$

The complex conjugate of this complex power is

$$S^{*}=P-jQ=\overline{V_R}^{*}\left(\frac{\overline{V_S}+\overline{V}_{SE}-\overline{V_R}}{jX}\right) \qquad (6)$$

Performing simple mathematical manipulations and separating real and imaginary components of Eq (6) the following expressions for real and the reactive powers received at the receiving end of the line are

$$P=\frac{V_SV_R}{X}\sin\delta+\frac{V_RV_{SE}}{X}\sin(\delta-\varphi_{SE})=P_O(\delta)+P_{SE}(\delta,\varphi_{SE}) \qquad (7)$$

$$Q=-\frac{V_R^{\,2}}{X}+\frac{V_SV_R}{X}\cos\delta+\frac{V_RV_{SE}}{X}\cos(\delta-\varphi_{SE})=Q_O(\delta)+Q_{SE}(\delta,\varphi_{SE})$$

(8)

For V_{SE} = 0 the above equations represent the real and reactive powers of the uncompensated system. As the UPFC unit's 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, and using in Eq (7) and (8) the real and reactive power received at bus R for the system with the UPFC unit is installed can be controlled between rotation of the series injected voltage phasor with RMS value of V_{SEmax} from 0 to 360^0 allows the real and the reactive power flow to be controlled within the boundary

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

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

(10)

III DESIGN OF PI2 CONTROLLER USING DE ALGORITNM

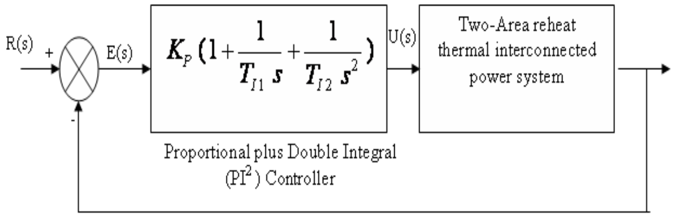

Figure 4: Closed loop control structure for AGC loop using PI^2 controller

The Integral gain in PI controller is limited relatively to small values because of the overshoot in transient's response. The disadvantage of integral controller is tends to make the system unstable because it responds slowly towards the produced error. A controller with two integrators is required to reduce this error to zero. The tuning of Proportional-Double Integral (PI^2) controllers, and relate the prescribed tuning parameters to the ultimate gain and period of the plant. In this study Proportional plus Double Integral (PI^2) controllers is used for AGC loop of an interconnected power system as shown in Fig 4. The PI^2 controllers are expressed in Laplace form as follows:

$$G_c(s)=k_P\;(1+\frac{1}{T_{I1}\;s}+\frac{1}{T_{I2}\;s^2}) \qquad (11)$$

In the present work an Integral Square Error (ISE) criterion is used to minimize the objective function which is defined as follows. The objective function is minimized with help of DE algorithm [12].

$$U_1\;=-K_p\;ACE_1-K_{I\,1}\int ACE_1\;dt-K_{I\,2}\int ACE_1\;dt \qquad (12)$$

$$U_2\;=-K_p\;ACE_2-K_{I\,1}\int ACE_2\;dt-K_{I\,2}\int ACE_2\;dt \qquad (13)$$

The Linearized model of two- area two- units interconnected reheat thermal power system considering GDB and GRC nonlinearities with UPFC and RFB units as shown in Fig 5.

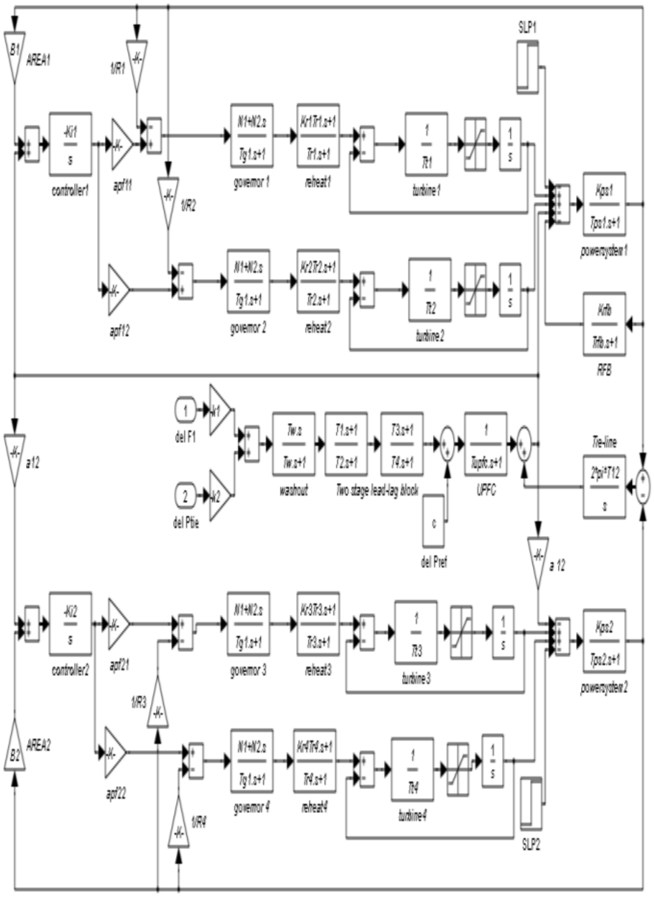

Figure 5: Linearized model of two- area two- units interconnected reheat thermal power system considering GDB and GRC nonlinearities with RFB and UPFC units

IV SIMULATION RESULTS AND OBSERVATIONS

In this study the active power model of UPFC controllers is fitted in the tie-line near area and RFB unit is installing in area 1 for LFC to study its performance of system. Simulation studies have been carried out in the system for 2 % step load perturbation in area 1 as shown in Fig 5. The nominal parameters are given in Appendix. The control parameters of PI^2 controller gain values ($K_{Pi}, K_{I1i,} K_{I2i}$) for each area and parameters of UPFC unit and are optimized simultaneously with help of DE algorithm. The results are obtained by MATLAB 7.01 software and 50 iterations are chosen for the convergence of the solution in the DE algorithm. The comparative transient performances of two-area Power System with RFB and UPFC units using PI^2 controller for given load perturbation are shown in Fig 6 and it can observed that the oscillations in area frequencies and tie-line power deviation have decreased to a considerable extent as compare to that of the system without RFB and UPFC units. Thus RFB coordinated with UPFC improves inertia mode and inter- area mode oscillations effectively.

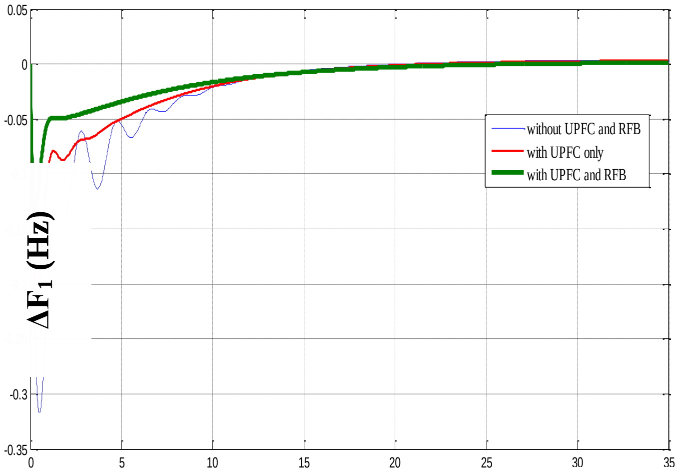

Figure 6 (A): ΔF_1 (Hz) Vs Time (s

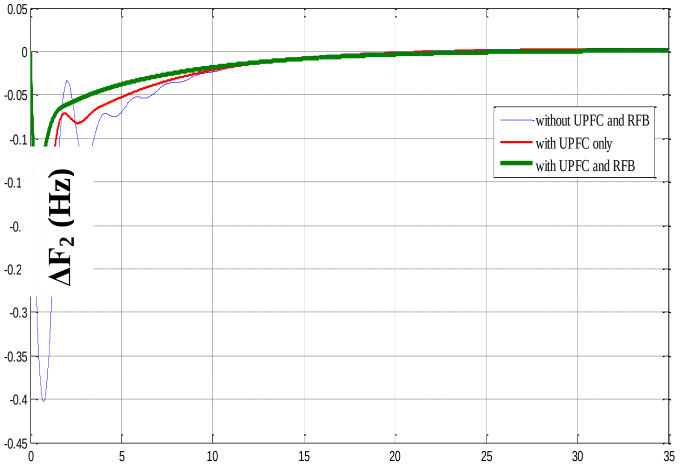

Fig 6 (B): ΔF_2 (Hz) Vs Time (s)

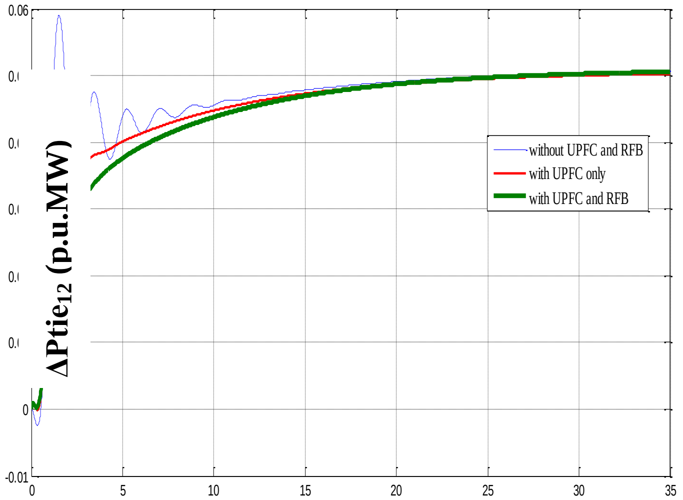

Figure 6(C): $\Delta Ptie_{12}$ (p.u.MW) Vs Time (s)

Figure-6: Dynamic responses of the frequency deviations and tie-line power deviations, for a two area LFC system considering GDB and GRC nonlinearities with and without UPFC and RFB

V CONCLUSION

.A sophisticated PI^2 controller based Load Frequency Control by RFB coordinated with UPFC controller has been proposed for a two area interconnected reheats thermal Power System considering GDB and GRC nonlinearities. The DE algorithm was employed to achieve the optimal parameters various combined control strategies. PI^2 controller with two integrators can able to reduce the area control error to zero even the system has complexities. The two integral time-constants values of the PI^2 controller which cause repeated roots in the controller transfer function, minimizing any adverse impact on the closed-loop stability as compared with PI controller. The proposed design concept effectively damps out the inertia mode and inter-area mode because of the coordinated control action of RFB and UPFC units and are found to be more effective to suppress the frequency deviations of the two area system

ACKNOWLEDGEMENT

The authors wish to thank the authorities of Annamalai University, Annamalainagar, Tamilnadu, India for the facilities provided to prepare this paper.

REFERENCES

1. Naimul Hasan, “An Overview of AGC Strategies in Power System”, International Journal of Emerging Technology and Advanced Engineering, Volume 2, Issue 8, pp. 56-64, 2012.

2. O.I. Elgerd and C.E. Fosha, "Optimum Megawatt-Frequency Control of Multi area Electric Energy Systems", IEEE Transactions on Power Apparatus and Systems, PAS-89, No.4, pp.556-563, 1970.
3. Lalit Chandra Saikia, J. Nanda and S. Mishra, "Performance comparison of several classical controllers in AGC for multi-area interconnected thermal system", Electrical Power and Energy Systems, Vol.33, pp.394-401, 2011.
4. R. Monroy-Loperena, I. Cervantes, A. Morales, and J. Alvarez-Ramirez, "Robustness and parameterization of the proportional plus double-integral compensator", Industrial Engineering Chemistry Research, Vol.38, pp.2013-2021, 1997.
5. I.A. Chidambaram and S. Velusami, "Design of decentralized biased dual mode controllers for load-frequency control of interconnected power systems considering GDB and GRC nonlinearities", Energy Conversion and Management, Vol.48, pp. 1691-1702, 2007.
6. T. Hiyama, "Decentralized load-frequency control under generation rate constraints", Electrical Engineering in Japan, Vol.102, No.4, pp.65-71, 1982
7. L.Gyugi, C.D. Schaunder, S.L. Williams, T.R. Reitman, D. R. Torgerson and A. Edris, "The Unified Power Flow Controller: A new approach to Power Transmission Control", IEEE Transactions on Power Delivery, Vol.10, pp.1085-1097, 1995
8. S.Arabi, P.Kundar and R.Adapa, "Innovative techniques in modeling UPFC for power system analysis", IEEE Transactions on Power System, Vol.15, pp.336-341, 2000.
9. I.A.Chidambaram and B.Paramasivam, "Control performance standards based load-frequency controller considering redox flow batteries coordinated with interline power flow controller", Journal of Power Sources, Vol.219, pp 292-304, 2012.
10. Tetsuo Sasaki, Toshihisa Kadoya, and Kazuhiro Enomoto, "Study on Load frequency Control using Redox Flow Batteries", IEEE Transactions on Power Systems, Vol.19, No.1, pp. 660-667, 2004.
11. S. Panda, Differential evolution algorithm for SSSC-based damping controller design considering time delay, J. Franklin Inst. 348 (8) (2011) 1903–1926.
12. Sidhartha Panda, Robust coordinated design of multiple and multi-type damping controller using differential evolution algorithm, Electr. Power Energy Syst. 33 (2011) 1018–1030.

APPENDIX –A

Data for the interconnected two- area thermal Reheat Power System with considering GDB and GRC nonlinearities [5]

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, $K_{p1} = K_{p2} = 120$Hz/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, $a_{12} = -1$, $\Delta P_{D1} = 0.02$ p.u.MW, $N_1 = 0.8$, $N_2 = -0.2$, $\Delta P_{gmax} = 0.03$ p.u.MW/min. Data for the UPFC unit [7] $T_{UPFC} = 0.01$ s; $T_w = 10$ s, Data for the RFB unit [10] :$T_{RFB} = 0$, $T_{di} = 0$, $T_{ri} = 0$