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Load Frequency Control for Two-Area Power System Considering GDB and GRC Nonlinearities with RFB and TCPS

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Abstract— **This paper proposes Load Frequency Control (LFC) of a two-area thermal reheat power system considering Governor Dead-Band (GDB) and Generation Rate Constraints (GRC) nonlinearities. The simultaneously presence of GDB and GRC, even with small load perturbation, the system becomes highly nonlinear and hence the optimization problem becomes rather complex. The quality of frequency and tie-line power responses reflect the time error and inadvertent interchanges respectively. Simple integral controllers are used in the LFC loop and the controller gains are optimized with Genetic Algorithm optimization technique. The proposed controller has been applied to the two-area interconnected power system with coordinated control action from Redox Flow Battery (RFB) and Thyristor Controlled Phase Shifter (TCPS) in order to achieve a better transient as well as steady state response and improved stability of the system. Simulation results reveal that the proposed controller with the coordinated control action between HES and TCPC units greatly reduces the over shoot/under shoot of the frequency deviations and tie- line power flow deviation. Moreover it reduces the control input requirements and the settling time of the output responses also reduced considerably.**

Keywords: *Governor Dead-Band, Generation Rate Constraints, Load Frequency Control, Redox Flow Battery and Thyristor Controlled Phase Shifter.*

I INTRODUCTION

The goal of Load Frequency Controller is to restore primary frequency regulation, return the frequency to its nominal value and minimize unscheduled tie-line power flows between neighbouring control area [1]. The operating point of a power system changes with time and hence the systems may experience deviations in nominal system frequency and scheduled power exchanges to other areas which may yield undesirable effects. Due to the sudden load perturbations which continuously disturb the normal operation of a power system, two variables of interest, system frequency and tie-line power exchange, undergo variations. To correct these steady state errors, supplementary control must adequately be given in both the areas. Based on the above objectives, the two variables such as tie-line power deviation added to frequency deviations weighted by a bias factor together by a linear combination to form a single variable called Area Control Error (ACE), which is used as the control signal for defining the LFC problem [2]. 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 [3]. 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 [4].

Most of the options proposed so far for the LFC have not been fruitfully implemented in practice due to system operational constraints associated with thermal power plants. 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 [5, 6]. The recent advances in power electronics have led to the development of the Flexible Alternating Current Transmission System (FACTS) devices which can be adopted as one of the most effective ways to improve power system operation controllability and power transfer limits [7]. This extra flexibility permits the independent adjustment of certain system variables such as power flow, which are not easily controllable. A Thyristor Controlled Phase Shifter (TCPS) is regarded as one of the versatile devices in the FACTS devices family which is

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expected to be an effective apparatus for the tie-line power flow control of an interconnected power system. It injects a variable series voltage to affect the power flow by modifying the phase angle [8].Thus, TCPS is essential to modulate the active power in power systems and its high speed operation makes it attractive to be used for the improvement system operation and control. Various optimization techniques have been applied to solve the LFC problem. These techniques are mostly based on the principle of local search in the feasible region solution. Some authors have applied GA technique to optimize the controller gains more effectively and efficiently than the classical approach [9]. In the study GA based LFC loop for two-area interconnected power system considering GDB and GRC nonlinearities with RFB and TCPS is considered.

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

2.1 Mathematical Modeling of Redox Flow Batteries unit

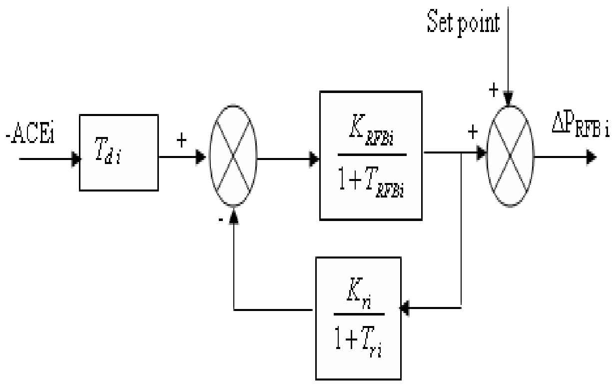

Figure 1: Redox Flow Battery System model

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 leveling 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 TCPS unit

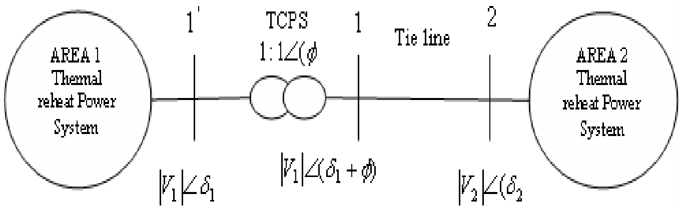

Figure 2: TCPS unit in a of two area interconnected power system

A TCPS is one of the FACTS devices that can change the relative phase angle between the system voltages therefore, the real power flow can be regulated to mitigate the frequency oscillations and enhance power system stability [8]. The TCPS is found to be superior to the governor system in terms of high-speed performance. When a sudden load perturbation occurs in power system, the TCPS quickly start control to suppress the peak value of the transient frequency deviation, governor systems responsively compensated for the steady state error of frequency deviation. Fig.2 shows the schematic diagram of the two-area interconnected reheat thermal power system with TCPS in series with the tie-line. The mathematical model of a TCPS unit for stabilization of frequency oscillations is derived from the power flow control characteristics of the TCPS unit. Resistance of the tie-line is neglected. Without TCPS unit, the incremental tie-line power flow from area 1 to area 2 can be expressed as

$$\Delta P^{o}_{tie12}(s) = \frac{2\pi T^{o}_{12}}{s}\left[\Delta F_1(s) - \Delta F_2(s)\right] \quad (1)$$

When a TCPS is placed in series with the tie-line, as in Fig.2, the current flowing from area 1 to area 2 can be written as

$$I_{12} = \left(\frac{|V_1|\angle(\delta_1+\phi) - |V_2|\angle\delta_2}{jx_{12}}\right) \quad (2)$$

Where, X_{12} is the line reactance, V_1 and V_2 are the bus terminal voltages. The active and reactive power flows at bus 1 are

$$P_{tie12} - jQ_{tie12} = V_1^* I = |V_1|\angle -(\delta_1+\phi)\left(\frac{|V_1|\angle(\delta_1+\phi) - |V_2|\angle\delta_2}{jx_{12}}\right) \quad (3)$$

Separating the real part of tie-line power in Eq (3)

$$P_{tie12} = \frac{|V_1||V_2|}{x_{12}}\sin(\delta_1 - \delta_2 + \phi) \quad (4)$$

In Eq (4) perturbing δ_1, δ_2 and ϕ from their nominal values δ^0, δ^0 and ϕ^0 respectively, we get

$$\Delta P_{tie12} = \frac{|V_1||V_2|}{x_{12}}\cos(\delta_1{}^0 - \delta_2{}^0 + \phi^0)\sin(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) \quad (5)$$

But $(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi)$ is very small and hence, $\sin(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) = (\Delta\delta_1 - \Delta\delta_2 + \Delta\phi)$,

Therefore,

$$\Delta P_{tie12} = \frac{|V_1||V_2|}{x_{12}}\cos(\delta_1{}^0 - \delta_2{}^0 + \phi^0)(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) \quad (6)$$

Let, $T_{12} = \frac{|V_1||V_2|}{x_{12}}\cos(\delta_1{}^0 - \delta_2{}^0 + \phi^0)$ (7)

Thus, Eq (6) reduces to

$$\therefore \Delta P_{tie12} = T_{12}(\Delta\delta_1 - \Delta\delta_2) + T_{12}\Delta\phi$$

It is known that $\Delta\delta_1 = 2\pi\int \Delta f_1 dt$ (8) *and* $\Delta\delta_2 = 2\pi\int \Delta f_2 dt$ (9)

From the Eqn (8) and Eqn (9),

$$\Delta P_{tie12} = 2\pi T_{12}\left(\int \Delta f_1 dt - \int \Delta f_2 dt\right) + T_{12}\Delta\phi \quad (10)$$

Laplace Transform of Eqn (10) is

$$\Delta P_{tie12}(s) = \frac{2\pi T_{12}}{s}\left[\Delta F_1(s) - \Delta F_2(s)\right] + T_{12}\Delta\phi(s) \quad (11)$$

It is evident from the Eqn (11), tie line power flow can also be controlled by controlling the phase shifter angle$\Delta\phi$. The phase shifter angle $\Delta\phi(s)$ can be represented as

$$\Delta\phi(s) = \frac{k\phi}{1 + sT_{tcps}}\Delta Error_1(s) \quad (12)$$

Where $k\phi$ is the Gain value of TCPS, T_{PS} is the time constant of TCPS unit. In this study, the input signal to the TCPS control logic is considered the frequency deviation of area 1 $[\Delta F_1]$. Thus the tie-line power flow perturbation becomes

$$\Delta P_{tie12}(s) = \frac{2\pi T_{12}}{s}\left[\Delta F_1(s) - \Delta F_2(s)\right] + T_{12}\frac{k\phi}{1 + sT_{tcps}}\Delta F_1(s) \quad (13)$$

III MODELING OF A TWO-AREA POWER SYSTEM CONSIDERING GDB AND GRC NONLINEARITIES WITH RFB AND TCPS UNIT

The power system considered in this work consists of two generating areas of equal capacities. Each area comprises of two thermal reheat generation units. Because the system is exposed to a small change in load during its normal operation, the linear model will be sufficient for its dynamic representation. The detailed transfer function models of speed governors and turbine are discussed and developed as per the IEEE Committee Report on Dynamic Models for Steam and Hydro Turbines in the Power System Studies. The Redox Flow Battery and Thyristor Controlled Phase Shifter units are found to be superior to the governor system in terms of the faster response against the frequency fluctuations as discussed in section-2. They are charged with suppressing the peak value of frequency deviations quickly against the sudden load change, subsequently the input to the governor system are updated with the required input for the compensation of the steady state error of the frequency deviations. Whereas 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 TCPS. Here, from the physical view point it is noted that the TCPS 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. The Linearized model of two- area interconnected reheat thermal power system with RFB and TCPS considering GDB-GRC nonlinearities as shown in Fig 3.

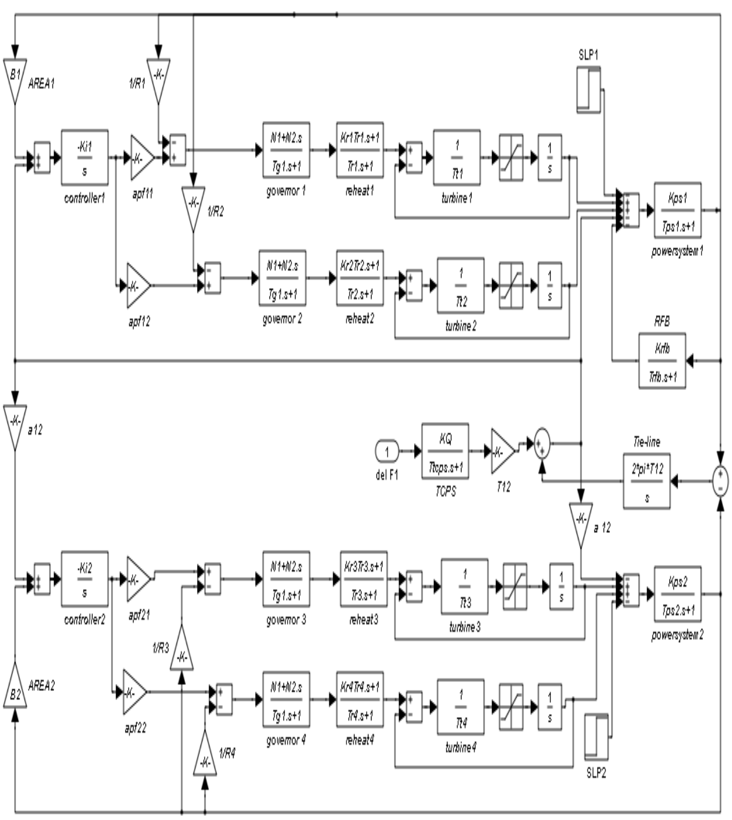

Figure 3: Linearized model of two-area two-units interconnected reheat thermal power system with RFB and TCPS units considering GDB and GRC nonlinearities

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IV DESIGN OF INTEGRAL CONTROLLER USING GENETIC ALGORITNM

The objective of LFC is to re-establish primary frequency regulation, restore the frequency to its nominal value as quickly as possible and minimize tie-line power flow oscillations between neighboring control areas. In order to satisfy the above requirement, gains values (K_{i1}, K_{i2}) of integral controller in LFC loop, gain value (K_{rfb}) of Redox Flow Battery, gain value (Kφ) and time constants (T_{tcps}) of Thyristor Controlled Phase Shifter are to be optimized to have minimum undershoot (US), overshoot (OS) and settling time (ts) in area frequencies and power exchange over tie-line. In the present work, an Integral Square Error (ISE) criteria are used to minimize the objective function defined as follows [10].

$$J = \int_0^T \{(\beta_1 \Delta f_1)^2 + (\beta_2 \Delta f_2)^2 + (\Delta P_{tie12})^2\} \qquad (14)$$

The objective function is minimized with help of Genetic Algorithm based optimization techniques and optimum values of integral gain settings of both equal areas for three case study (without and with TCPS only and with TCPS and RFB), gain value (K_{rfb}) of Redox Flow Battery, gain value (Kφ) and time constants (T_{tcps}) of Thyristor Controlled Phase Shifter are tabulated in Table 1. The Genetic Algorithm is the part of the evolutionary algorithms family, which are meta- heuristic computational methods. Genetic Algorithm Optimization methodology is already discussed in [9].

V SIMULATION RESULTS AND OBSERVATIONS

Genetic Algorithm optimization technique is adopted for optimizing various parameters in two equal area interconnected thermal reheat power system considering GDB and GRC nonlinearities having different types of controls like Integral control, Integral-TCPS combined control, and Integral-TCPS-RFB combined control. Simulation studies have been carried out in the two - area interconnected multi- units thermal reheat power system for 2% step load perturbation in area1 shown in Fig.3. The nominal parameters are given in Appendix. The gain values of the integral controller, gain value of RFB, gain value and time constants of TCPS, are optimized using GA with MATLAB 7.01 software. It can be noted that GA is made to run several times and the optimal set of controller parameters are selected. Results of the controller parameter set values without, with TCPS and TCPS and RFB are listed in the in Table 1. The method works with a set of solutions from one generation to the next, and not a single solution, thus making it less likely to converge on local minima. The solutions developed are randomly based on the probability rate of the genetic operators such as mutation and crossover as the initial solutions would not dictate the search direction of GA. It may concluded that RFB coordinated with TCPS offers lower optimal values of objective function (J) and gives better stability. These controllers are implementing in an interconnected two-area power system with GDB and GRC nonlinearities. The comparative transient response for three case studies is shown in Fig 4; it can be observed that the oscillations in area frequencies and tie-line power deviations have decreases to a considerable extent as compare to that of the system without TCPS and RFB. The settling time 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 2. Moreover the RFB located in area 1 has a coordinated action with TCPS controllers ensures better transient performances as RFB improves the inertia mode and inter area oscillation.

Table 1: Optimized parameters of the two area interconnected Power System

Test System with GDB and GRC	Integral Gain (Ki_1=Ki_2)	Cost function (J)	Time constants (Ttcps)	TCPS gain value (Kφ)	RFB gain value (Krfb)
Without TCPS and RFB	0.182	0.845	---	---	---
With TCPS only	0.268	0.649	0.504	1.548	---
With TCPS and RFB	1.648	0.138	0.265	1.648	0.735

Table 2: Comparison of the system performance for the three case studies

Test System with GDB and GRC	Setting time (τ_s) in sec			Peak over / under shoot		
	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1 (Hz)	ΔF_2 (Hz)	ΔP_{tie} (p.u.MW)
Without TCPS and RFB units	24.845	34.873	30.481	0.7421	0.7295	0.1527
with TCPS unit only	18.789	28.542	25.458	0.5319	0.4104	0.0097
with TCPS and RFB units	15.478	20.478	22.147	0.3967	0.2243	0.0752

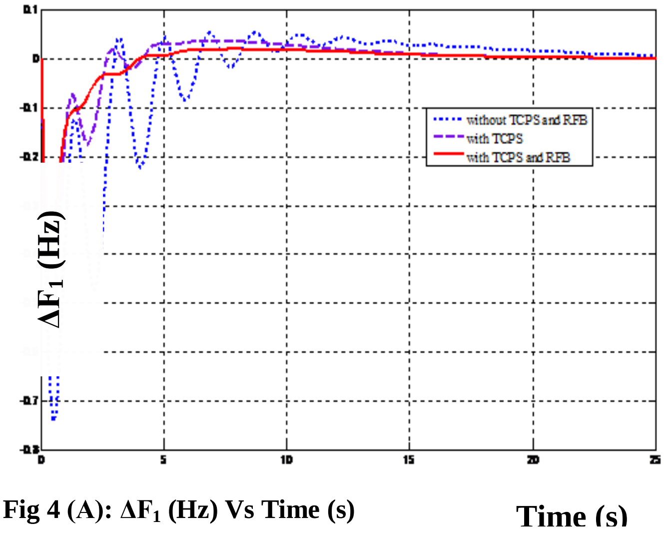

Fig 4 (A): ΔF_1 (Hz) Vs Time (s)

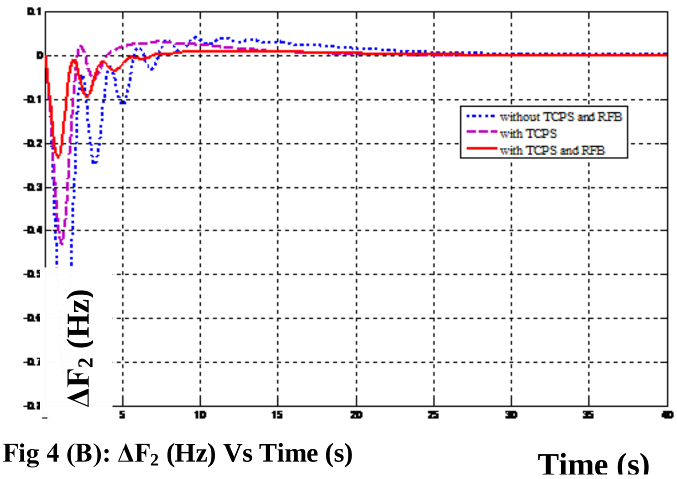

Fig 4 (B): ΔF_2 (Hz) Vs Time (s)

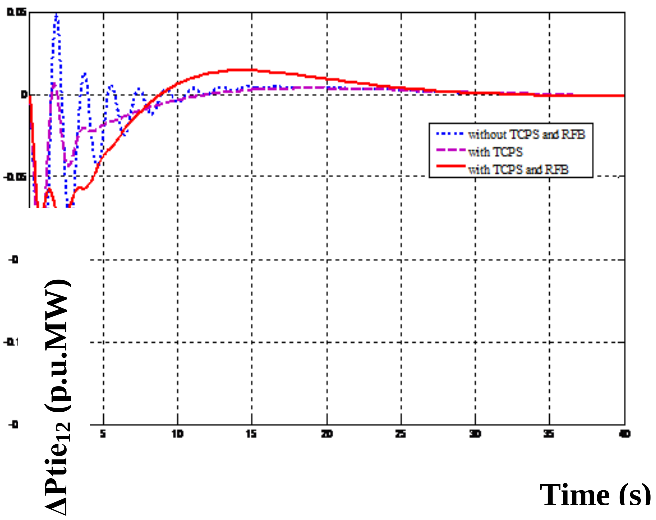

Figure-5 (C): $\Delta Ptie_{12}$ (p.u.MW) Vs Time (s)

Figure-5: 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 TCPS and RFB

VI CONCLUSION

The Genetic Algorithm Optimization Technique was employed to achieve the optimal parameters various combined control strategies. In this study, a sophisticated Load Frequency Control by Redox Flow Batteries coordinated with TCPS controller has been proposed for a two area interconnected reheat thermal Power System considering GDB and GRC nonlinearities. Simulation results reveal that the first peak frequency deviation of both areas and tie-line power oscillations following sudden load disturbances in either of the areas can be suppressed a controlling the phase angle of the TCPS unit. The RFB contributes a lot in promoting the efficiency of overall generation control through the effect of the use in load levelling and the assurance of LFC capacity after overload characteristic and quick responsiveness. It may be conclude that the design concept of damping the inertia mode and inter-area mode, the RFB coordinated with TCPS is effective to suppress the frequency deviation of two area system simultaneously. A control strategy has been proposed to control the TCPS phase angle which in turn controls the inter-area tie-line power flow.

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APPENDIX –A

Data for the interconnected two- area thermal Reheat Power System with considering GDB and GRC nonlinearities [3]

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, ΔP_{D1} = 0.02 p.u.MW, N_1 = 0.8, N_2 = -0.2, ΔP_{gmax} = 0.03 p.u.MW/min. Data for the TCPS unit [8]: T_{ps} = 0.1 s, $K\varphi$ = 1.5 rad / Hz, Φmax = 10º, Φmin = - 10º. Data for the RFB unit [6] :T_{RFB} = 0, T_{di} = 0 , T_{ri} = 0