ROLE OF STORAGE DEVICES IN FREQUENCY REGULATION SERVICES OF REALSTIC MULTISOURCE DEREGULATED POWER SYSTEM

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Abstract: *This article demonstrates the effect of storage devices on frequency regulation services in two-area interconnected power system, having multiple thermal–hydro–gas mixed generating units in deregulated power environment. To obtain optimal dynamic responses of area frequencies oscillations following load disturbances, Capacitive Energy Storage (CES) units have been fitted in both the areas along with Thyristor Controlled Phase Shifter (TCPS) in series with the tie-line. Integral Square Error (ISE) criterion is used to find the optimal gain of the integral controller. The effect of coordinated action of CES and TCPS units has been demonstrated on the area frequency, tie line power and generated power of different units. The performance of the system has been examined in different contract scenarios in a deregulated electricity environment. Analysis reveals that CES unit with TCPS unit give better dynamic response by reducing the tie line power and area frequency oscillations.*

Keywords: *- Automatic Generation Control (AGC); capacitive energy storage; deregulation; thyristor controlled phase shifter*

1. INTRODUCTION

Restructuring in power system has brought major reforms in the sector and managing power trade has become easier by eliminating the monopoly of vertically integrated utilities (VIU). However, participation of many power producers including Independent Power Producers (IPP) and various distributors have also made the power system operation more complex [1]. The frequently changing load and lack of perfect coordination between various stakeholders is a challenge and any sudden variation in the load may cause frequency deviations and tie line power error. It is therefore necessary to maintain the frequency and tie line power exchange of each area within acceptable limits following variation in the load. This can be achieved by AGC which can stabilize the frequency and power fluctuation in the interconnected system and maintain the net change by minimizing the mismatch of different area [2].

In realistic interconnected power system, the total generation comprises of different sources like thermal, nuclear hydro, wind, solar gas etc. However, nuclear plants are usually operated as base load plant close to their maximum generation power output with no participation in the system AGC. Gas power generation is also a viable option for meeting the variable load demand during peak hours. Thus, the natural choice for AGC falls on either thermal or hydro generating units [3].

A lot of research has been done by different researchers in traditional AGC with and without including deregulation scenario. Elgerd and Fosha have proposed a two area non reheat thermal system to study AGC problem [4]. Cohn has presented a comprehensive philosophy for improving the AGC performance of interconnected systems [5]. Kothari et al. [6] worked on the AGC problem by implementing integral type supplementary controllers in hydro-thermal power system. Perhaps Nanda et al. [7] were the first to present comprehensive study of AGC of an interconnected hydro-thermal power system having classical controller in continuous-discrete mode.

Many strategies have been employed for AGC of power system to maintain the stable frequency and constant tie line power exchange during normal and abnormal operation under different deregulated environmental conditions. P.K. Hota et al. have proposed AGC of multisource power generation under deregulated environment having two area thermal-gas plant. For this, PID controller is optimized with (DE) algorithm and Genetic Algorithm (GA) technique [8].In [9], comparative analysis between different controllers based on intelligent techniques are shown to illustrate their robust performance for AGC in three area restructured power. In [10], Impact of Redox Flow Battery (RFB) with Opposition-based Harmonic Search (OHS) technique to attain stable dynamics response in multisource interconnected power system operated under different conditions in deregulated power environment is studied. Impact of TCPS in two area power system under deregulation scenario has been examined in [11]. Comparative study of Thyristor controlled series compensator (TCSC) with TCPS and Static Synchronous Series Compensator (SSSC) controller for AGC in two area interconnected multisource power system having thermal-hydro-gas is studied in [12].Imperialistic Competition Algorithm to design the value of gain of integral controller for Load Frequency Control (LFC) of SSSC and CES based multi area system consisting of diverse sources has been investigated in [13]. A hybrid DE–PS technique over DE and GA for load frequency control under deregulated scenario by considering Unified power flow controller (UPFC) and RFB has been demonstrated in [14]. Effect of TCSC in frequency control services of two area multi-source power system is presented in [15]. The dynamic performance by optimizing PI controller through intelligent techniques for interconnected power systems with non-linearity has been shown in [16]. AGC with TCSC including Superconducting Magnetic Energy Storage (SMES) units of two area with fuzzy PID controller under various operating conditions has been investigated in [17].The role of Inter-line Power Flow Controller (IPFC) with RFB for LFC of two area having T-T units under various possible transactions in the competitive electricity market has been shown in [18]. In [19], Fractional-order Proportional–Integral–Derivative (FOPID) controller has been presented for AGC of a three area thermal system under deregulated scenario. In [20], a coordinated design of TCPS and SMES is studied for frequency stabilization services of two area deregulated power systems having DFIG based wind farm. Impact of TCPS for LFC of two area thermal-hydro-gas (THG) power System has been presented in [21].The effect of regulation (R) on the frequency deviation response in single area power system having different generating units has been examined in [22]. In this, actual power system (hydro power plants operational in KHOZESTAN, IRAN)) are also considered for analysis to show the effectiveness of proposed controller. Authors in [23] deal with the comparative study of between SMES, TCPS and SSSC controllers in AGC for a two-area power system having hydro units. In [24], PID controller gain is optimized by using hybrid particle swarm optimization (HPSOCFA) for AGC of four area TT restructured power system. Role of coordination action of TCPS and SMES storage for LFC in two-area THG interconnected power systems with integral has been shown in [25]. Frequencies regulation services by using integral controller in THG power system under deregulated conditions has been studied in [26]. In [27], the dynamic performance of CES and TCPS for AGC of two area hydro-diesel system as connected to hydro-thermal power system using GA/particle swarm intelligence based optimization controller has been studied. AGC by using TCPS and fuzzy logic controller in deregulated hydrothermal power system has been examined in [28].

Literature study reveals that Flexible AC Transmission Systems (FACTS) devices have the potential to improve power system dynamics performance because they have more flexibility to operate in several undesirable conditions. They are very effective in enhancing the power system stability and manage smooth power flow in an interconnected power system [29]. In dynamic operations of power system, manual control to maintain these balances would be impossible. So, a superior control system is required to maintain the frequency at its nominal values and for matching system generation response under random load variations Thus, in deregulated environment also, AGC play an important role to stabilize the frequency and power fluctuation in the interconnected system and maintain the net change by minimizing the mismatch of different area [30].

In view of the above literature survey, an attempt is made in this article to study the effect of CES and TCPS unit in a realistic multi area multi generating unit power system comprising of reheat thermal, hydro and gas generating units along with all non-linarites like governor dead band (GDB) and generation rate constraint (GRC) constant in each area under deregulated market scenario and subsequently to compare the performance of the proposed system with and without CES units for frequency regulation services. The analysis has been carried out considering pool transactions, bilateral transactions and contract violation cases under deregulated environment. The dynamic response of the proposed system have been obtained and compared under deregulated market scenario.

The rest of the paper has been organised as follows: Section 2 discusses the structure of the test power system under investigation. Section 3 deals with mathematical model of TCPS. Section 4 and 5 covers the modelling of CES and simulation results respectively; conclusion is summarized in section 6.

2. SYSTEM INVESTIGATED

In deregulated environment, the possible ways in which the transactions of power take place are poolco-based transaction, bilateral exchange and Power Exchange (PX). Planning and operation of the power system with emergence of different entities to fit the new deregulated market scenarios for ensuring reliability and security is necessary. Hence, the AGC provides control to these power exchanges between neighbouring control areas by fixing the frequency oscillation and by regulating the tie-line power flow of the entire system [31].

To get an accurate insight into the AGC problem, a realistic transfer function model of two-area six-unit power systems with different power generating units [26] including the physical constraint like GDB non-linearity for thermal plant and GRC for both hydro and thermal plants. Following recent works [12, 32], the Fourier coefficients of N1 and N2 in transfer function of back-lash type GDB are N1=0.8 and N2=0.2π/p, respectively. The GRC of 10% /min for the thermal units is considered for both rising and falling rates. For the hydro unit, typical GRC of 270%/min and 360%/min for raising and falling generation is considered respectively [22, 33]. Due to the presence of large thermal plants, their participation factor is generally large in the range of 50–60%. The participation factors of hydro units are about 30%. As, gas generating power stations are few, their participation is usually low which is about 10–15% [30]. In the present study, participation factors for thermal and hydro are assumed as 0.5747 and 0.2873 respectively. For gas unit same participation factors of 0.1380 are assumed. CES units are fitted in both the areas and TCPS unit in series with tie line under deregulated environment as shown in fig. 1.

In the present system, both area-1 as well as area-2 consist of identical combination of three power generating unit viz. thermal, hydro, and gas. Whole study has mainly focused on finding the effect of CES unit with TCPS unit in restructured deregulated market for achieving optimal dynamic performance in the proposed power system. Control area-1 consists of three Generation Companies (GENCOs) namely GENCO-1, GENCO-2 and GENCO-3 of different capacity with two distribution companies namely DISCO-1 and DISCO-2. Area-2 is also comprised three generators namely GENCO-4, GENCO-5 and GENCO-6 and two Distribution Companies (DISCOs) namely DISCO-3 and DISCO-4.

In restructured scenario, the GENCOs are accessible for transmission of power to DISCOs in his same area as well as DISCOs in other areas. The DISCOs have the flexibility to purchase power from different GENCOs at competitive prices. The various combinations of contracts for exchange of power between DISCOs and GENCOs in both areas are in accordance with the concept of a Distribution Participation Matrix (DPM). DPM highlight the contractual relationship between various GENCO-DISCO for possible type of contractual arrangement.

In the DPM matrix, no. of columns designate the no. of DISCOs and the no. of rows designates the no. of GENCOs which Contract power. Each entry in this matrix can be thought of as a fraction of a total load contracted by n^{th} DISCO (column) toward m^{th} GENCO (row). The sum of all the entries in a column of this matrix is unity [33].Contracted load of every DISCOs is represented by each element of the cpf-matrix and this demand is fulfilled by corresponding GENCO involved in the contract. In traditional AGC mechanism, governor and turbine of generator must respond with any variation in the load in whole power system. However in deregulated power system, only the contracted GENCO should respond to meet the demand of the specific DISCO to regulate the load variation. [8, 9].

Thus, an information is conveyed to specify the corresponding contracted demand between any DISCO and GENCO. However, this information is not communicated as fast and accurately with load demand in traditional situation. This communication is very significant for the GENCOs to follow. At the same time, DISCOs having contracts with GENCOs in another area, the signal giving demand must fit the scheduled power flows over the tie-lines. This change in the scheduled power introduces the tie-line power flow deviations and constitutes the ACE which is used as the input controlling signal [10]. Thus, local loads in a restructured environment have to be modified as given below:

$$\Delta P_{D1} = \Delta P_{L1} + \Delta P_{L2} \tag{1}$$

$$\Delta P_{D2} = \Delta P_{L3} + \Delta P_{L4} \tag{2}$$

Where ΔP_{D1} and ΔP_{D2} are the corresponding local load of control area-1 and area-2 respectively. ΔP_{L1}, ΔP_{L2}, ΔP_{L3} and ΔP_{L4} are the p.u load of DISCO-1,2,3,4 respectively.

Similarly when any DISCO violate the contract by demanding more power than its predefined values, then this unspecified contract demand is reflected as uncontracted excess load and this demand is fulfilled only by the GENCO which belong to the same area as the DISCO. In this case, the local uncontracted load is specified and defined as:

$$\Delta P_{D1} = \Delta P_{L1} + \Delta P_{L2} + \Delta P_{L1UC} \tag{3}$$

$$\Delta P_{D2} = \Delta P_{L3} + \Delta P_{L4} + \Delta P_{L2UC} \tag{4}$$

Where ΔP_{Luc} is the uncontracted load demand both areas.

The scheduled steady state power exchange on the tie-line can be given as follows:

$\Delta P_{Tie,12}{}^{Scheduled} =$ (Discos demand in area-1 from Gencos in area-2) - (Discos demand in area-2 from Gencos in area-1) (5)

Mathematically, equation (5) can be defined as given by (6):

$$\Delta P_{Tie,12}{}^{Scheduled} = \sum_{m=1}^{3} \sum_{n=3}^{4} cpf_{mn} \Delta P_{\ln} - \sum_{m=3}^{4} \sum_{n=1}^{3} cpf_{mn} \Delta P_{\ln} \tag{6}$$

The actual tie-line power can be represented as given by (7)

$$\Delta P_{Tie,12}{}^{actual} = \frac{2\pi T_{12}}{s} (\Delta f_1 - \Delta f_2) \tag{7}$$

The tie-line power error can now be written by equation (8)

$$\Delta P_{Tie,12} error = \Delta P_{Tie,12}{}^{actual} - \Delta P_{Tie,12} scheduled \tag{8}$$

The tie line error $\Delta P_{Tie,12} error$ reduces to zero at steady state condition, because the actual tie-line power flow reaches the scheduled power flow. Each GENCOs supply its generated or contracted power which is represented by (9) as:

$$\Delta P_{gm} = \sum_{n=1}^{4} cpf_{mn} P_{\ln} \tag{9}$$

Where m=1 to 6;

The area control error (ACE) is a linear combination of weighted frequency deviation in an area and tie-line power error as given by equation (10) below:

$$ACE_1 = B_1 \Delta f_1 + \Delta P_{Tie12}{}^{error} \text{ and}$$

$$ACE_2 = B_2 \Delta f_2 + \Delta P_{Tie21}{}^{error} \tag{10}$$

Proposed power system contains three GENCOs in each area which participate in LFC according to their ACE signal. Coefficients that distribute ACE to GENCOs are termed as ‘‘ACE Participation Factors (apfs)’’. The sum of participation factors in any control area is equal to unity.

Hence, apf_{11} , apf_{12} , and apf_{13} ,are considered as area participation factor in area-1 and apf_{21}, apf_{22} , apf_{23} are in area-2.

The linear dynamics behavior of the proposed power system considered for LFC in deregulated environment can be expressed by state variable differential equation [11, 26] as shown below

$$\overline{X} = AX + BU + \Upsilon P + \Upsilon' P' \quad (11)$$

Where X, U, P and P' are the state, control, disturbance and uncontracted load disturbance vectors, respectively, and A, B, Υ and Υ' are constant matrices of compatible dimensions associated with them. The matrices for the system under study can be represented by equation (12)-(15).

$$X=[\Delta f_1 \Delta f_2 \Delta P_{tie12actual} \Delta P_{m21} \Delta P_{g22} \Delta P_{t22} \Delta P_{m22} \Delta P_{m23} \Delta P_{m11} \Delta P_{g12} \Delta P_{t12} \Delta P_{m12} \Delta P_{m13} \Delta V_2 \Delta V_1$$
$$\Delta P_{g11} \Delta P_{t11} \Delta P_{g21} \Delta P_{t21} \Delta P_{g13} \Delta P'_{g13} \Delta P_{g23} \Delta P'_{g23} \Delta P_{t23} \Delta P_{t13}]^T \quad (12)$$

$$U = [U_1 U_2]^T \quad (13)$$

$$P = [\Delta P_{L1} \Delta P_{L2} \Delta P_{L3} \Delta P_{L4}]^T \quad (14)$$

and $$P' = [\Delta P_{L1UC} \Delta P_{L2UC}]^T \quad (15)$$

The realized state variables for power system model are represented in Fig.1.

2.1 Design of optimal AGC controller:

In order to attain optimal transient performance in the proposed power system, the gain (K1, K2) of integral controllers in the AGC loop with CES and TCPS units are to be optimized by Integral Square Error (ISE) criterion. Optimum value of CES and TCPS unit parameters are also settled by using ISE. In the present work to minimize the objective function a "performance index J" is defined as given below [13]:

$$J = \sum \left[\Delta f^2{}_1 + \Delta f^2{}_2 + \Delta p^2{}_{tie} \right] \Delta T \quad (16)$$

Where Δf_1 and Δf_2 are the discrete value of incremental frequency change in area-1 and area-2 respectively; ΔP_{tie} is the tie line exchange value, ΔT is a given time interval for taking sample. Transfer function analysis is performed for obtaining the samples values from their respective plots.

3. MODELLING OF TCPS

A TCPS is an electrical device which controls the system voltage by changing the relative phase angle between them. Therefore, it can maintain the real power flow in the system and mitigate the high frequency anomaly and enhances the power system stability. Resistance of the tie-line is neglected due to tie line high reactance to resistance ratio [11, 20]. The incremental tie-line power flow change between area-1 to area-2 can be represented by (17) below.

$$\Delta P_{tie}^{\circ}(s) = \frac{2\pi T^{\circ}_{12}}{S} [\Delta F_1(s) - \Delta F_2(s)] \quad (17)$$

After including a TCPS unit in series with the tie-line, the real power flow exchange between area-1 to area-2 is given as

$$\Delta P_{tie} = \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1 - \delta_2 + \varphi) \quad (18)$$

Perturbing δ_1, δ_2 and φ from their nominal values $\delta^{\circ}{}_1$, $\delta^{\circ}{}_2$ and φ° respectively and following a small signal approximation approach, the tie line power flow perturbation becomes as shown by (19).

$$\Delta P_{tie} = T_{12}(\Delta\delta_1 - \Delta\delta_2) + T_{12}\Delta\varphi \quad (19)$$

Where $T_{12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta^{\circ}{}_1 - \delta^{\circ}{}_2 + \varphi^{\circ})$

Further, we also know, angular deviation can be given as

$$\Delta\delta_1 = 2\pi \int \Delta F_1 dt \text{ and } \Delta\delta_2 = 2\pi \int \Delta F_2 dt \quad (20)$$

Hence, Laplace transformation of eq. (20) yields

$$\Delta P_{tie}(s) = \frac{2\pi T_{12}}{S} [\Delta F_1(s) - \Delta F_2(s)] + T_{12}\Delta\varphi(s) \quad (21)$$

As per (21), the phase shifter angle (Δφ) regulate the tie-line power flow exchange. The phase shifter angle Δφ(s) can be defined as given in [22].

$$\varphi(s) = \frac{K_{\varphi}}{1 + sT_{ps}} \Delta Error \quad (22)$$

where, ΔF_1 is the frequency variation in area-1 is chosen as the ΔError signal in this work and K_{φ} and T_{PS} are the gain and time constant of the TCPS respectively, as given in [28].Therefore, eq. (21) can be rewritten as

$$\Delta P_{tie}(s) = \frac{2\pi T_{12}}{S} [\Delta F_1(s) - \Delta F_2(s)] + T_{12} \frac{K_{\varphi}}{1 + sT_{ps}} \Delta F_1(s) \quad (23)$$

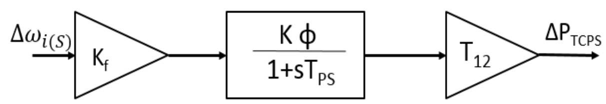

Fig. 2: Transfer function model of TCPS a frequency stabilizer.

4. MODELLING OF CES

CES unit is an energy storage device integrated with power conversion system which included rectifier/inverter and capacitor (a super capacitor or a cryogenic hyper capacitor) to store the energy with some protective devices .During normal operating conditions, capacitor stores energy in its plates and during any abnormal condition such as load change, the capacitor gets discharged and releases its energy into the grid in a fraction of time. Due to this, the governor and different control mechanisms begin operating to set the power system to the new equilibrium condition. When the system returns to its steady state, the capacitor again charges to its initial value of voltage by utilizing some portion of the surplus energy within the system. CES has energy efficiency nearly equal to 98%. The only losses being considered are the energy losses due to the power conversion system, internal leakage and self-discharge. Thus, a capacitive energy storage system is also an excellent energy storage device to enhance the stability of any hybrid power system [34, 35].

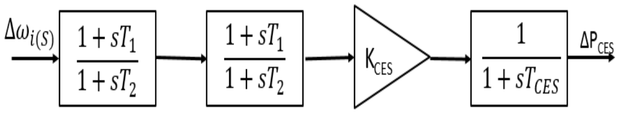

Fig. 3: Transfer function model of CES a frequency stabilizer

Fig.3 represents the transfer function model of CES. The CES as frequency stabilizer consist of gain block having time constant $T_{1,}T_2, T_3, \text{and}\, T_4$ respectively. In the present work, CES units have been incorporated in area-1 and area-2 in order to stabilize frequency oscillations. The incremental change in the power of CES is expressed as given below:

$$\Delta P_{CES} = \left[\frac{K_{CES}}{1+sT_{CES}}\right]\left[\frac{1+sT_1}{1+sT_2}\right]\left[\frac{1+sT_3}{1+sT_4}\right]\Delta\omega_i(s) \qquad (24)$$

Where i=1,2 ; K_{CES} and T_{CES} are the gain and time constant of CES respectively. The ACE of each area is fed as control signal to the CES unit which is used to supply the power proportional to the change.

5. SIMULATION AND RESULTS

The proposed two area power system with diverse sources of power generation including CES and TCPS unit under study having competitive market scenario has been developed in SIMULINK environment in MATLAB 8.5.0. A realistic model of power system incorporated with different generating unit like reheat thermal, hydro and gas in each area is evaluated regarding non linearity effect of GDB and GRC. A series simulation has been performed including CES unit in both the areas and TCPS unit in series to minimize tie line power flow. Various analyses have been carried out for possible realistic electricity contract in deregulated environment. The plant parameters have been given in appendix (A) [11, 26]. The load disturbance of 0.05% step change has been considered in each DISCO which results in to total step load disturbance equal to 0.1%. Each GENCO participates in AGC as defined by its area participation factors (apfs). The simulation is carried out on the basis of the contract between the GENCOs and DISCOs as per the DPM. Three different case studies have been conducted which are as follows:

A. Poolco based transaction

In this scenario, each GENCO can participate in AGC according to their area participation factor (apfs) and at the same time each DISCO has contract with their same area GENCOs, i.e. the apfs for thermal, hydro and gas unit are apf_{11}=0.5747, apf_{12}=0.2873, and apf_{13}=0.1380 so that $apf_{11}+apf_{12}+apf_{13}$=1.0 in area-1. Similarly, apf_{21} =0.5747, apf_{22}=0.2873 and apf_{23}=0.1380 are the apfs in area-2 for thermal, hydro and gas unit respectively so that $apf_{21}+apf_{22}+apf_{23}$=1.0.

In this case, it is considered that the load is varied in area-1only, i.e. the load is demanded by DISCO-1 and DISCO-2 only. The load demand by the DISCOs in area-1 has been assumed 0.05 pu MW each, i.e. $\Delta P_{L1} = \Delta P_{L2}$=0.05 pu MW so that a total load change 0.1pu MW occur in area 1. In area 2, $\Delta P_{L3} = \Delta P_{L4}$=0 pu MW. So according to equation 1 and 2, power demand at both areas are as given below:

$$\Delta P_{D1} = (0.05+0.05) = 0.1 \text{ p.u MW}$$

$$\Delta P_{D2} = (0+0) = 0 \text{ p.u MW}$$

All DISCOs and GENCOs in the system under study having deregulated market scenario make their contract as per the following DPM for this case study:

$$DPM = \begin{bmatrix} 0.3333 & 0.3333 & 0 & 0 \\ 0.3333 & 0.3333 & 0 & 0 \\ 0.3333 & 0.3333 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad (25)$$

Performance analysis in the form of both areas frequency deviation, tie-line deviation and generation response of different generating units to meet the load demand of the proposed system has been obtained for the assumed contract in fig.4 to fig.7.

Fig. 4. shows the variation of frequencies in both area corresponding to the load variations under unilateral contract. The CES units are added in both the areas and are coordinated with TCPS unit in series with tie-line to study their effect on the system performance. It is observed from the results that the frequency deviations after including CES and TCPS units have lesser oscillations and lower settling time. From the comparative analysis of the waveforms it can be concluded that better dynamic performance is obtained by implementing proposed storage devices in the two area multi generation unit power system.

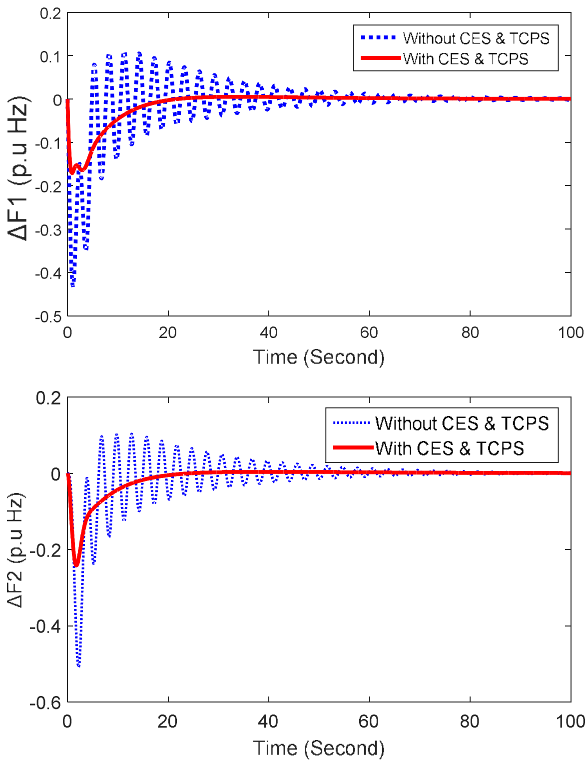

Fig. 4.Dynamics response of both areas frequencies with poolco based contract

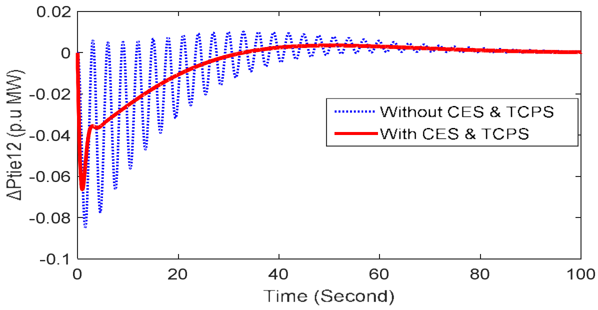

Fig.5.Variation in actual tie-line power flow with poolco based contract

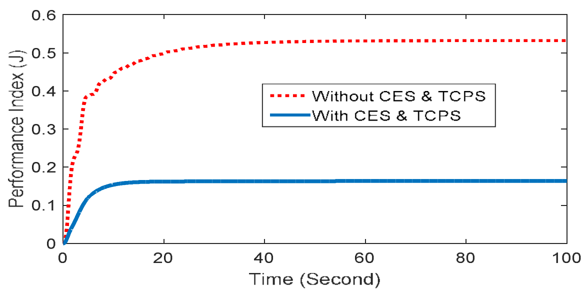

Fig. 6 Performance index with poolco based contract

Fig.5 shows the deviation in tie line power after a sudden load change of 0.1 pu in area-1 having CES and TCPS unit in the proposed power system. The results show that actual tie line power flow deviation after load change gets damped easily due to TCPS unit.

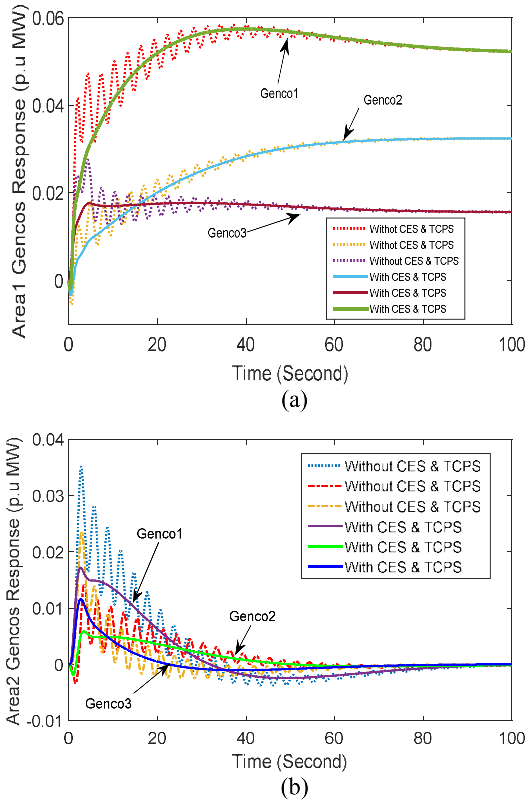

Fig. 7.Area- and area-2 Gencos generation response with and without CES and TCPS unit under poolco based contract

DISCOS of area-1 demand power from their own area GENCOS so the GENCOS must generate contracted power according to their contract. Fig.7 (a & b) show the generation response of area-1 and area-2 GENCOs respectively. Obtained waveform show that the area-1 GENCOS i.e GENCO1, GENCO2 and GENCO3 generate power according to the demand and their contract participation factor. Deviation is improved due to CES unit in the system and generators quickly attain their steady state stage. Fig 7(b) show that there is no demand by the DISCOs in area-2. Hence, change in generated power by all GENCOs corresponding to this area is zero at steady state. Generation response outputs of various GENCOS also depict that the system having CES unit have better dynamic response as compared to the system without CES units. It can be observed from the results obtained above that the system attains better dynamics performances in terms of settling time, peak overshoot and peak rise time value of $\Delta F_1, \Delta F_2$ and ΔP_{tie} after implementation of CES and TCPS unit.

Table 1 shows the comparative analysis during unilateral transaction with and without CES and TCPS unit in the proposed system under study. Various parameter like peak overshoot, undershoot and settling time of different waveforms obtained viz. frequency response of both areas, response of tie line power, different generating units output power response is studied. It can be observed that better dynamic performance is achieved due to the presence of CES and TCPS unit in the proposed system.

TABLE 1. Comparative analysis with and without CES unit during unilateral contract.

Parameter	Waveform	Without CES	CES	Percentage Improvement (%)
Settling Time	F1	95.87	37.18	61.21
	F2	87.19	33.81	61.11
	P-tie	96.81	90.97	6..01
Peak Overshoot	F1	0.1097	0.0037	96.62
	F2	0.1003	0.0042	95.81
	P-tie	0.0099	0.0033	66.6
Peak Undershoot	F1	-0.4258	-0.170	60.07
	F2	-0.5071	-0.241	52.47
	P-tie	-0.084	-0.065	22.61

B. Bilateral based transaction

The phenomenon of transactions between a DISCO and a GENCO in any other area is known as bilateral transactions. All DISCOs and GENCOs in the system under study having deregulated market scenario make their contract as per the following DPM for this case study:

$$DPM = \begin{bmatrix} 0.2 & 0.1 & 0.3 & 0 \\ 0.2 & 0.2 & 0.1 & 0.1666 \\ 0.1 & 0.3 & 0.1 & 0.1666 \\ 0.2 & 0.1 & 0.1 & 0.3336 \\ 0.2 & 0.2 & 0.2 & 0.1666 \\ 0.1 & 0.1 & 0.2 & 0.1666 \end{bmatrix} \quad (26)$$

It is assumed that each DISCO in their control areas demands 0.05 pu MW power from the GENCOs as per their contracted load demand matrix shown in eq. (31). Each GENCO participate in AGC to fulfill this load demand as per the following apfs: $apf_{11} = apf_{21}$=0.5747, $apf_{12} = apf_{22}$ =0.2873, and $apf_{13} = apf_{23}$ 0.1380. Thus, a total load disturbance of area-1 is 0.1 pu MW and in area-2 is 0.1 pu MW respectively. So, according to equation 2 and 3, power demand at both areas are as given below:

$$\Delta P_{D1} = (0.05 + 0.05) = 0.1 \text{ p.u MW}$$

$$\Delta P_{D2} = (0.05 + 0.05) = 0.1 \text{ p.u MW}$$

In bilateral contract, the system performance has been studied with instantaneous changes in load demand between various GENCOs and DISCOs. Various possible transactions between DISCOs and GENCOs of both areas are being simulated according the above given DPM.

Fig. 8 shows the frequency deviations in both areas under sudden load change in deregulated market. The results reveal better dynamics performance due to coordinated action of CES and TCPS in terms of lesser settling time, lower peak overshoot and peak rise time. Frequency deviations in both areas are quickly damped after implementation of CES units.

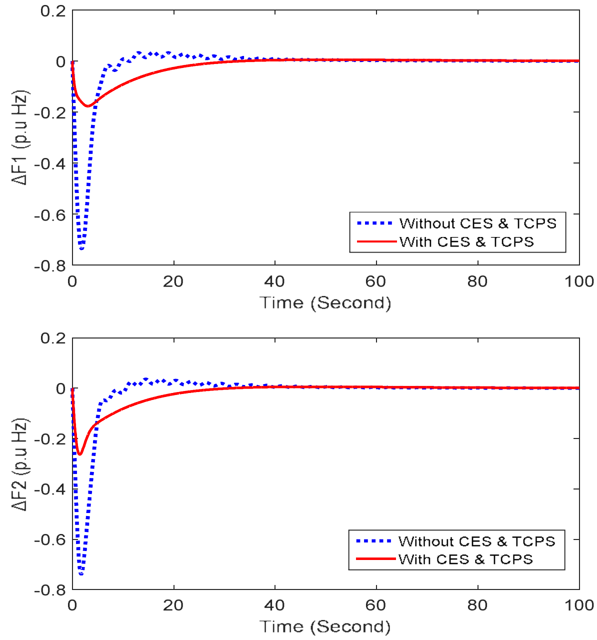

Fig. 8.Dynamics response of both areas frequencies with bilateral based contract

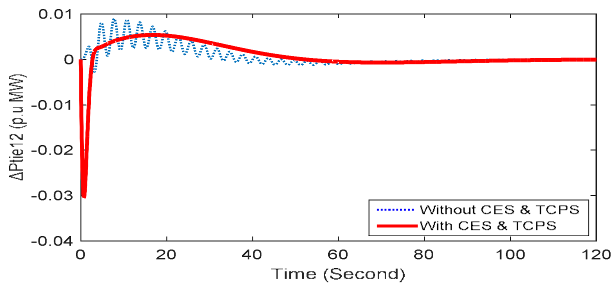

Fig.9.variation in actual tie-line power flow with bilateral based contract

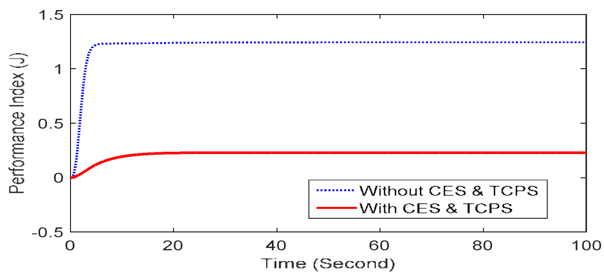

Fig. 10 performance index under bilateral based contract

Fig.9 shows the variation in actual tie-line power error with bilateral contract. The tie line power deviation is also improved by including TCPS in proposed two area multi-generating unit power system. TCPS quickly damped the oscillations and damped the tie line power to zero. Hence, the effectiveness of TCPS unit is depicted in the results.

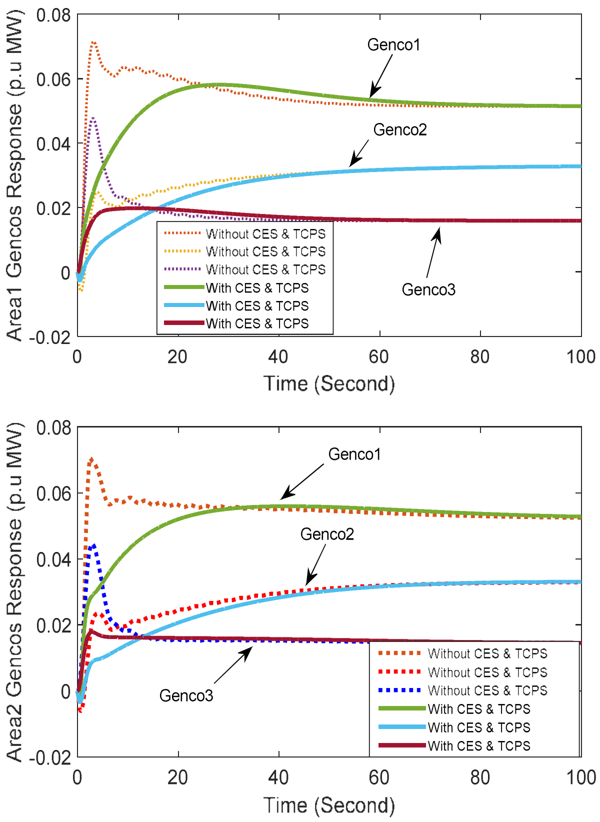

Fig. 11.Area-1and area-2 Gencos generation response with and without CES and TCPS unit under bilateral contract case

TABLE 2. Comparative analysis with and without CES unit during bilateral contract.

Parameter	Waveform	Without CES	CES	Percentage Improvement (%)
Settling Time	F1	40.0	34.97	12.57
	F2	41.01	33.50	18.31
	P-tie	75.35	67.63	10.24
Peak Overshoot	F1	0.0322	0.0027	91.61
	F2	0.0793	0.0049	93.82
	P-tie	0.0088	0.0053	39.77
Peak Undershoot	F1	-0.7236	-0.176	75.64
	F2	-0.7275	-0.256	64.79
	P-tie	-0.0022	-0.030	00

The dynamic response of variations in generated power of various GENCOs to fulfil the load demand in both the areas is shown in the Fig.11. Each GENCO generates power according to the transaction contract with different DISCOs. Oscillations in the form of peak overshoot and settling time is completely vanishes out after including CES unit in the proposed power system. The comparative results show the superiority of the proposed work after including CES and TCPS units. The oscillations are more quickly damped after including CES unit as compare to system without CES unit. The setting time and peak overshoot are lesser in the system having CES with TCPS unit.

C. *Contract violation case*

Contract violation occur as DISCO deviates from the pre-existing contract by demanding excess power form the GENCOs than what has been specified in the contract. This additional power demand must be fulfilled by the GENCOs operating in the same area as that of the DISCO belongs [10]. This type of unspecified contract demand which does not fall under predefined contract seems like a local load of that control area where the contract violation has taken place.

In case-B again and the excess demand by the GENCOs under contract violation case has been taken as 0.05 (pu MW). The DPM as used in bilateral based transaction has been considered here as well. Due to excess demand by the DISCOs, the total load demand in area-1 becomes 0.15pu MW. The total local load in area-2 remains the same as in case 2, because there is no uncontracted load in area-2. So according to equations 4 and 5, power demand at both areas are as given below:

$$\Delta P_{D1} = (0.05 + 0.05 + 0.05) = 0.15 \text{ p.u MW}$$

$$\Delta P_{D2} = (0.05 + 0.05) = 0.1 \text{ p.u MW}$$

The different dynamic responses of the investigated contract violation based system having CES units in both the areas and TCPS unit in series with the tie line are presented from the Fig. 12 to Fig. 15.

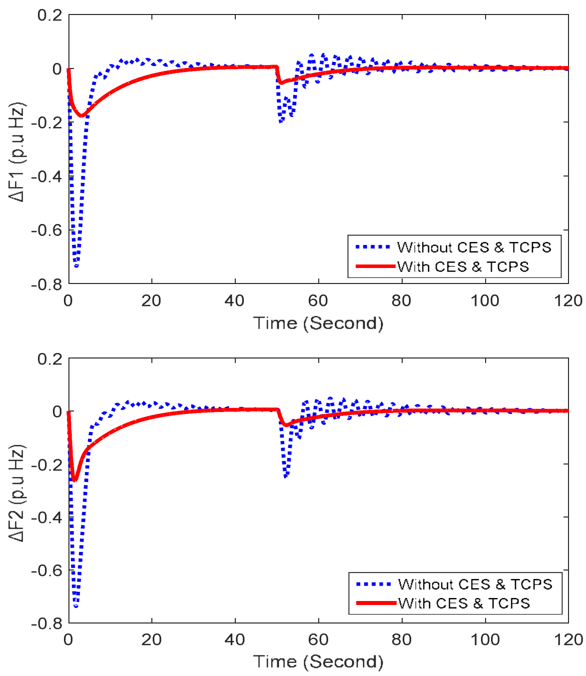

Fig.12.Dynamics response of areas frequencies under contract violation case.

Fig.12 shows the frequency deviations after violation of contract by an excess load of 0.05 pu MW after 50 second by the GENCOs of area-1. The frequency deviations due to this load change is damped quickly after including CES unit in both the areas with TCPS unit in series with tie line.

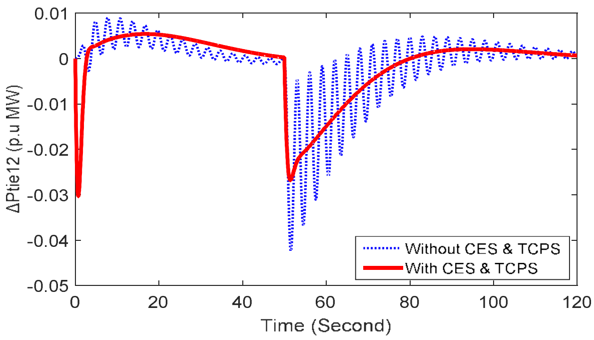

Fig.13.variation in actual tie-line power flow under contract violation case

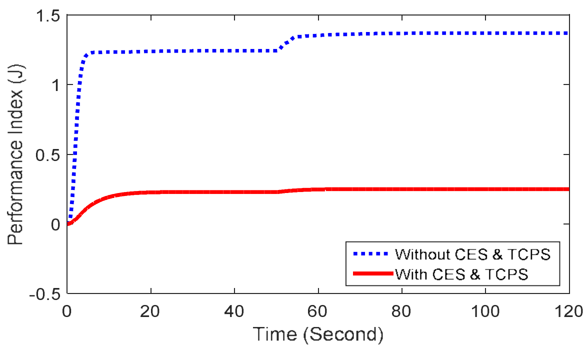

Fig. 14 performance index with contract violation case

Fig.13 depicts the results of tie-line power variations with and without TCPS in series with the tie line. Results show the effectiveness of the TCPS unit in damping the tie-line oscillations.

Generated power dynamics responses of various GENCOs in two areas under contract violation case have been shown in the Fig.15. Generation responses from all GENCOS are clearly reflected in outputs due to excess power demand in both areas. The generators change their generation response suddenly to compensate the extra power demand of the DISCOs. The deviation in power is very less when CES and TCPS work in coordination. The results clearly demonstrate the significant improvement in system dynamic performance in terms of lesser undershoot and overshoot in frequency oscillation, lesser settling time and rise time values.

An extensive analysis is carried out by comparing the performance index value of the system with and without CES units. Fig 6, fig.10 and fig.14 shows the performance index value of the system in unilateral, bilateral and contract violation case respectively. It is found in all the cases that the performance index value of the system with CES unit is much lower as compare to the system without CES unit which confirm the superiority of the proposed method.

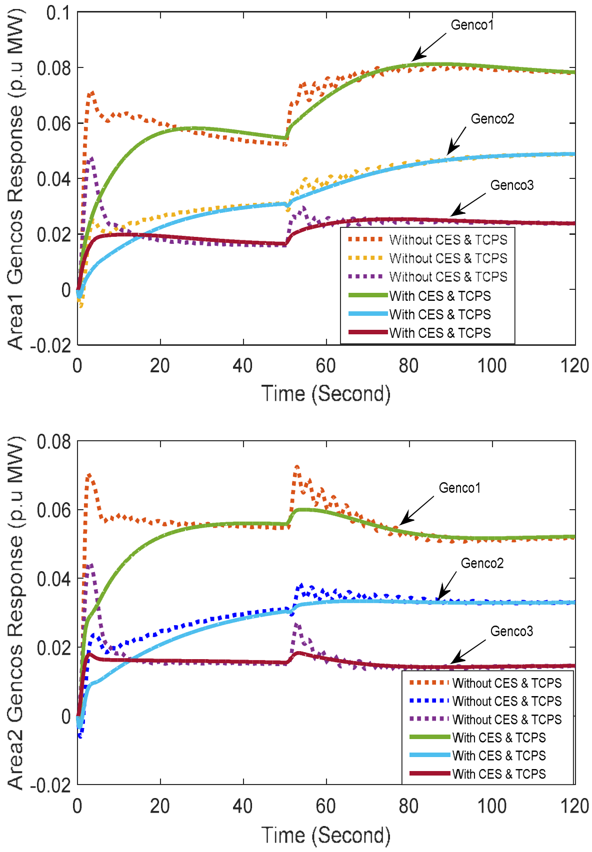

Fig.15 Area-1 and area-2 GENCOs generation response with and without CES and TCPS unit under contract violation case

TABLE 3. Comparative analysis with and without CES unit during contract violation case.

Parameter	Waveform	Without CES	CES	Percentage Improvement (%)
Settling Time	F1	114.5	89.66	21.69
	F2	111.8	87.02	22.16
	P-tie	124.3	115.1	7.40
Peak Overshoot	F1	0.03514	0.0055	84.34
	F2	0.0356	0.0059	83.42
	P-tie	0.0087	0.0053	39.08
Peak Undershoot	F1	-0.7276	-0.176	75.81
	F2	-0.7312	-0.261	64.30
	P-tie	-0.0421	-0.029	31.11

Percentage improvement analysis during bilateral transaction and contract violation case with and without CES and TCPS unit in the proposed system is given in Table 2 and Table 3.Various parameter like peak overshoot, undershoot and settling time of different obtained waveform namely frequency response of both areas, response of tie line power, different generating units output power response is studied. Improvement in results show that the system attains better dynamic performance due to the presence of CES and TCPS unit.

6. CONCLUSION

The storage devices play a very important role in enhancing the dynamic performance of deregulated power system due to their fast response time. In this paper, the system performance is investigated during various power transactions that take place under deregulated environment of power system between various stakeholders. The coordinated operation of CES and TCPS decreases the tie line error and deviations of the area frequencies in terms of peak time, maximum peak-overshoot and settling time. The application of CES and TCPS units assure the AGC requirement in all transaction cases including poolco, bilateral and contract violation case. The obtained results and performance index values of the system in different transaction performed under competitive electricity market also validate the effectiveness of the storage devices in proposed realistic power system. It can be concluded that the AGC of the multi-area multi-units power system in the deregulated environment is improved by including CES unit with TCPS unit by suppressing area frequency oscillation and tie line power exchange of power system as the response time of storage devices and different units complement each other.

APPENDIX-A

Various model constants used for simulation in proposed system:

Power system data

P_{rt} =2000 MW; P_L =1000 MW; f =60 Hz; a_{12} =-1

D = 0.008333 pu MW/Hz; K_{PS} =120 Hz/pu MW

T_{PS} =20 sec; $B_1 = B_2$ =0.4312 pu MW/Hz; T_{12} =0.0433

Thermal system data=

K_r =0.3; T_r =10 sec; T_{sg} =0.08sec; T_t =0.3 sec

R_i =2.4 Hz/pu MW where i=1 to 6

Hydro system data

T_{gh} = 0.2 sec; T_{rs} =5 sec; T_{rh} = 28.75 sec; T_{ws} =1.0 sec

Gas unit data:

C_g =1; B_g =0.05 sec; X_g =0.6 sec; Y_g =1.0 sec;

T_F =0.23 sec; T_{Cr} =0.01 sec; T_{Cd} =0.2 sec

TCPS unit data

T_{PS} =0.01 sec; K_θ =0.4 rad/Hz; $\theta_{\max} = 10^0$; $\theta_{\min} = -10^0$

CES Unit data

K_{CES} =0.3, T_{CES} =0.046; T_1 =0.279, T_2 =0.026

T_3 =0.0411, T_4 =0.39

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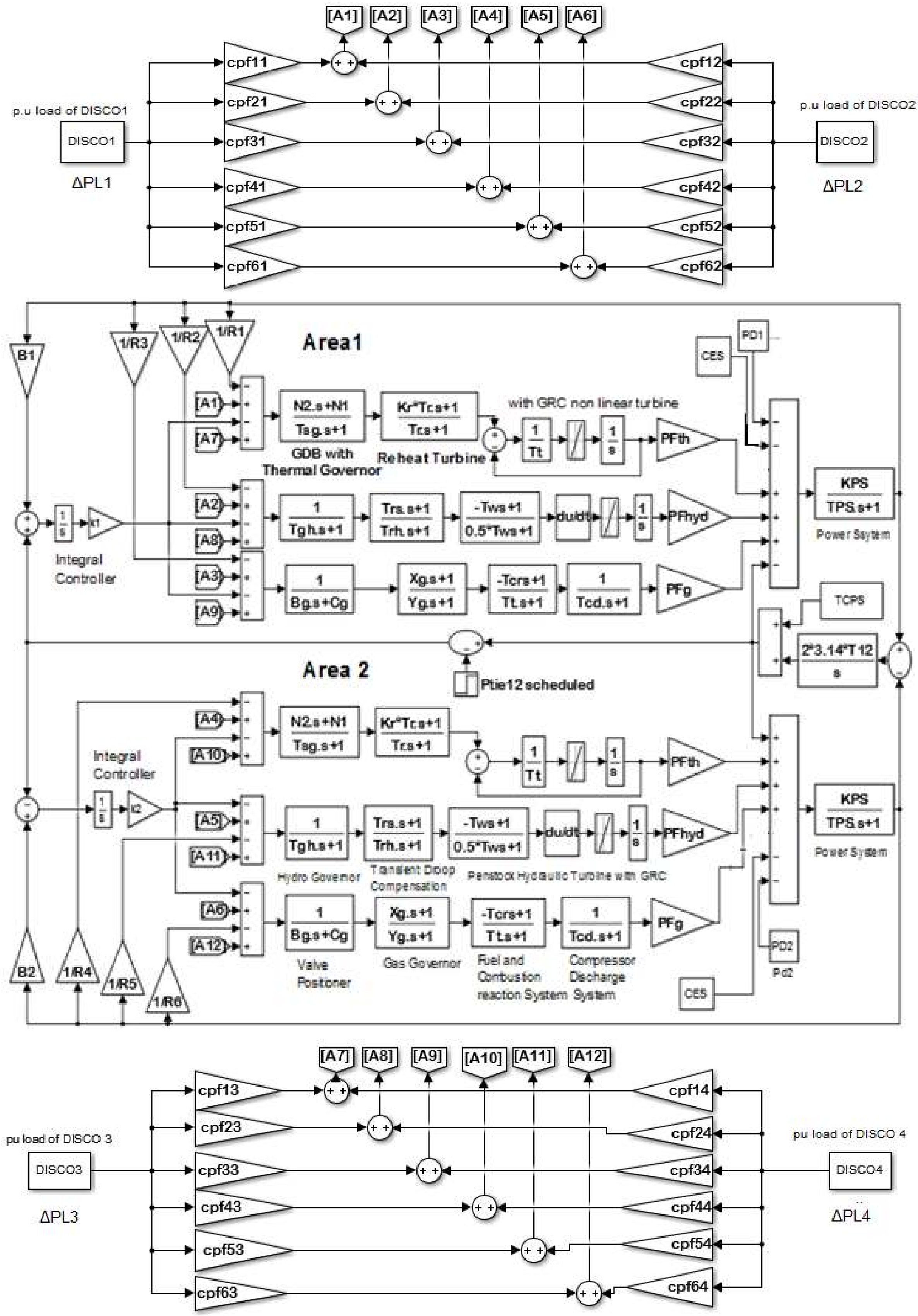

Fig. 1: MATLAB/Simulink model of two-area multi-source deregulated power system with GRC and GDB having CES and TCPS systems