

LFC For Deregulated Power Systems With GDB Non-Linearity and SMES Units Using ACS Algorithm

Ramesh Kumar Selvaraju¹, Ganapathy Somaskandan²

¹Assistant Professor, Department of Electrical Engineering,

Annamalai University, Annamalai nagar – 608 002, Tamil Nadu, India.

²Professor, Department of Electrical Engineering, Annamalai University, Annamalai nagar – 608 002, Tamil Nadu, India

Abstract

A new design of Artificial Cooperative Search (ACS) algorithm based optimal load frequency controller for interconnected power systems in deregulated environment with Super Conducting Magnetic Energy Storage (SMES) units and considering Governor Dead Band (GDB) nonlinearity is proposed in this paper. The inclusion of SMES units provide bulk energy storage and release to the power systems, significantly improving the system transients of frequency and tie-line power deviations against small load disturbances. The GDB is included as it has a considerable effect on the performance of the governor. In the presence of GDB nonlinearity, the performance of the system is associated with large overshoot and longer settling times. Hence it is significant to consider the GDB nonlinearity while designing the controller. The Artificial Cooperative Search Algorithm is a new two-population based global search optimization algorithm, developed for solving complex numerical optimization problems. The proposed controller designed using ACS algorithm fulfils the main objective of Load Frequency Control (LFC) problem in deregulated environment, namely to propose a suitable controller such that a generator can take part in load following as well as share the portion of uncontracted power demanded by the customer. Simulation studies are conducted on a two area interconnected power system model with GDB nonlinearity and SMES units. Simulation results reveal that the presence of SMES units along with the proposed controller tuned using ACS algorithm improves the system transient responses of the deregulated power system in the presence of system nonlinearity and with different bilateral contracts.

Index Terms: Artificial Cooperative Search algorithm, Deregulated Power System, Governor Dead Band, Load Frequency Control, Super Conducting Magnetic Energy Storage.

Introduction

Load frequency control serves as an important ancillary service in the deregulated power environment. It is an essential mechanism in power system design and operation, which balances generated power and demand in each area to maintain the system frequency and the tie-line power exchanges between the areas at their prescribed values. Under deregulated environment, the existing power system structure has changed in such a way that it enables the emerging of specialized industries for generation (GENCO), transmission (TRANSCO), distribution (DISCO) and independent system operator (ISO) as an unbiased coordinator to balance reliability with economics. But still the common LFC objective, restoring the frequency and net tie-line interchanges to their desired values for each control area remains the same [1]. In the presence of small load variations and with the optimal controller gains, the frequency and tie-line power deviations persist in the power system for a much longer duration. During such situations, the governor may no longer be able to absorb the frequency deviations in shorter time duration due to its slow response [2]. An active power source with fast response such as Super Conducting Magnetic Energy Storage (SMES) unit is expected to be the most effective measure to compensate for the sudden load changes [3]. To damp out the oscillations quickly, SMES units are included in the LFC system under deregulated environment.

The Governor Dead Band (GDB) is defined as the total magnitude of a sustained speed change within which there is no change in valve position. The limiting value of dead band is specified as 0.06%. The speed-governor dead band has a significant effect on the performance of the governors and it has a destabilizing effect on the transient performance of the system. In most of the LFC analysis, the effect of the Governor Dead Band (GDB) nonlinearity is neglected for simplicity. But for a realistic analysis of the performance of power system, the GDB nonlinearity should be included as it has a considerable effect on the system amplitude and settling time of the oscillations [4, 5]. In this paper, the effect of GDB non-linearity has been included in the LFC of proposed de-regulated power system along with SMES units.

Recently, with the increasing size and complexity of the existing interconnected power systems, many techniques have been developed for design of LFC controllers in deregulated environment taking into account the bilateral contracts on the dynamics. Most of these techniques are based on the conventional proportional plus integral (PI) control technique [6]. The conventional PI controllers are still popular with the power industry because of their inherent simplicity, easy realization and robust nature. But the conventional method of tuning the PI controllers is time consuming. The most recent advancement is the application of soft computing techniques to the load frequency control of interconnected power systems having nonlinear models and continuously changing operating conditions [7]. In this paper, a new soft computing technique, namely, artificial cooperative search algorithm has been proposed for obtaining the optimal PI controller values for the proposed LFC system in deregulated environment.

LFC Model In Deregulated Environment

The structure of electrical utilities has changed dramatically after the induction of deregulation principles. Before deregulation, the ancillary services such as scheduling, system control and dispatch, reactive supply and voltage control from generation sources, regulation and frequency response, energy imbalance and operating reserve – spinning were provided by a single utility called as control area. Each control area has its own generating resources, transmission and distribution capacities located within its boundary. After deregulation, the new deregulation framework permits new companies to emerge namely, generation companies (GENCO's), transmission companies (TRANSCO's), distribution companies (DISCO's), and independent system operator (ISO). To resolve any difference between different companies, an independent contract administrator is preferred [8].

To improve the efficiency of operation of the existing power system scenario, deregulation principles have been introduced into the power system structure. In deregulated environment, the GENCOs and DISCOs can have various combinations of bilateral contracts in between themselves. The DISCO Participation Matrix (DPM) can be used to realize the bilateral contracts among various GENCOs and DISCOs. The details of the contracts between the GENCO and DISCO are provided by DPM. The number of rows in DPM is equal to the number of GENCOs and the number of columns in DPM is equal to the number of DISCOs in the deregulated scenario. Each entry of DPM is a fraction of a total load power contract between a DISCO and GENCO in the system. The total sum of all the entries of DPM column is unity [9].

$$\sum_j \text{cpf}_{ij} = 1 \tag{1}$$

The proposed deregulated power system is a two-area thermal power system with SMES units and GDB nonlinearity in deregulated scenario as shown in Figure.1. The corresponding DPM matrix is as given below, where cpf represents the contract participation factor. The off diagonal entries in the DPM represent the demand of DISCO in one area with the GENCO in another area.

$$\text{DPM} = \begin{bmatrix} \text{cpf}_{11} & \text{cpf}_{12} & \text{cpf}_{13} & \text{cpf}_{14} \\ \text{cpf}_{21} & \text{cpf}_{22} & \text{cpf}_{23} & \text{cpf}_{24} \\ \text{cpf}_{31} & \text{cpf}_{32} & \text{cpf}_{33} & \text{cpf}_{34} \\ \text{cpf}_{41} & \text{cpf}_{42} & \text{cpf}_{43} & \text{cpf}_{44} \end{bmatrix}$$

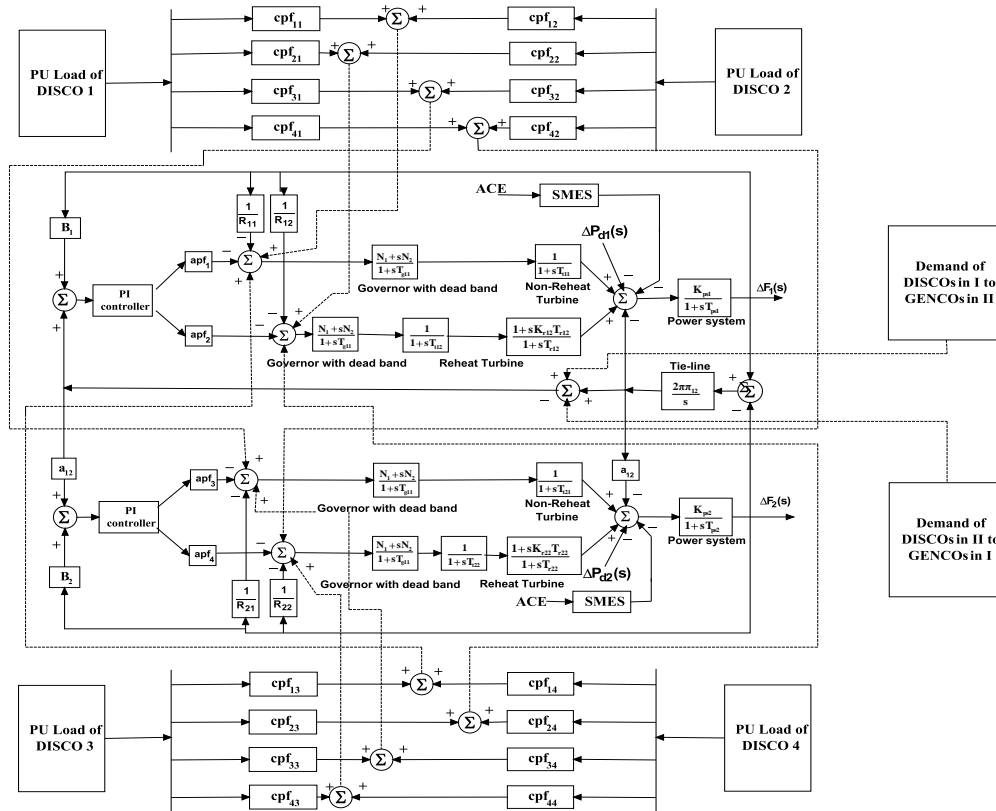


Figure 1: Block diagram of two area interconnected deregulated power system with SMES units and GDB nonlinearities

SMES System

The configuration of thyristor controlled SMES unit is shown in Figure.2. A superconducting inductance coil and a 12 pulse bridge converter connected to a transformer are present in each SMES unit. The bridge controller monitors the exchange of energy between the superconducting coil and power system. During normal operating state of the grid, the superconducting coil is charged to a level less than the full capacity of the coil from the grid. The DC magnetic coil and ac grid are connected through a power conversion system which consists of an inverter/rectifier. Once the coil is charged to its set point, the superconducting coil conducts current, which supports an electromagnetic field, with no loss.

The temperature of the SMES coil is maintained below the critical temperature value by immersing in liquid helium. When there is an increase in the load, the energy stored in the coil is immediately released through the convertor to the power system as an alternating current. Immediately, the power system control mechanisms start working to set the power system to its new equilibrium condition, the coil charges back to its initial value of current. Similarly during the sudden decrease of loads, the coil gets charged towards its full value, thus absorbing some portion of the excess

energy in the system, and as the system returns to its steady state, the excess energy absorbed is released back and the coil current attains its set point [10].

In LFC operation, the sensed area control error (ACE) is used to control the dc voltage E_d across the inductor coil. In this study, inductor voltage deviation of SMES unit of each area is based on ACE of the same area in power system. Moreover, the inductor current deviation is used as a negative feedback signal in the SMES control loop. So, the current variable of SMES unit is intended to be settling to its steady state value [11]. The schematic diagram of SMES unit is shown in Figure.2. Figure.3 shows the transfer function block diagram of SMES unit.

The equations of inductor voltage and current deviation of SMES unit of area I ($i=1, 2 \dots N$) in Laplace domain are as follows

$$\Delta E_{di} = K_{oi} \frac{1}{1+sT_{dci}} \left[\sum_i \Delta F_i + \Delta P_{tie12} \right] - K_{Idi} \frac{1}{1+sT_{dci}} \Delta I_{di} \quad (2)$$

$$\Delta I_{di} = \frac{1}{sL_i} \Delta E_{di} \quad (3)$$

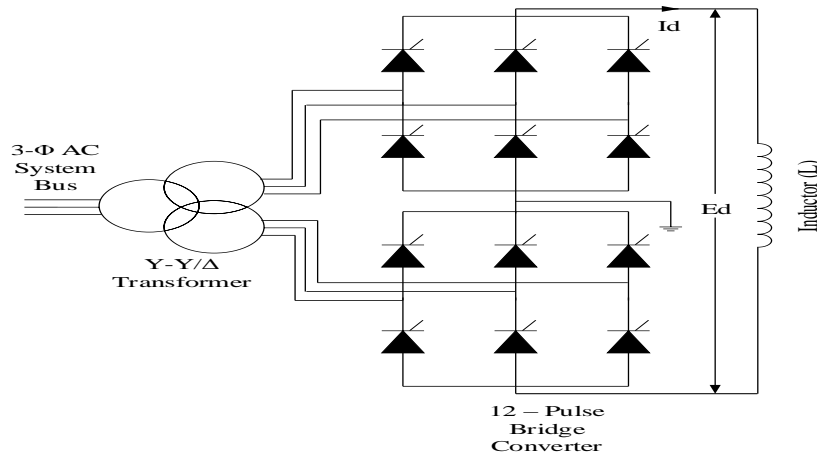


Figure 2: Schematic diagram of SMES Unit

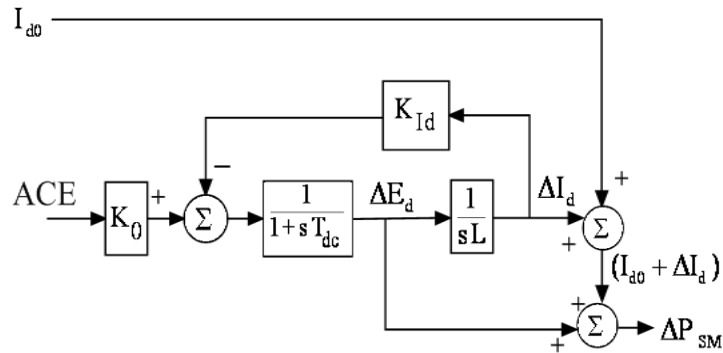


Figure 3: Block diagram of SMES unit

Where ΔE_{di} is the incremental change in converter voltage, ΔI_{di} is the incremental change in SMES current, K_{Idi} is the gain of the feedback ΔI_{di} , T_{dci} is the converter time delay, K_{oi} is the gain constant and L_i is the inductance of the coil. The deviation in the inductor real power ΔP_{sm} is expressed as given below

$$\Delta P_{smi} = \Delta E_{di} I_{dio} + \Delta I_{di} E_{di} \quad (4)$$

The energy stored in SMES at any instant in time domain is given by

$$W_{smi} = \frac{L_i I_{di}^2}{2} \quad (5)$$

With suitable control, the SMES unit can effectively reduce the frequency and tie-line power oscillations following sudden small load perturbations in power system.

Statement of The Problem

The dynamic behavior of the LFC system is described by the state space equation;

$$\dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{B}\mathbf{U} + \gamma\mathbf{D} \quad (6)$$

Where \mathbf{X} , \mathbf{U} and \mathbf{D} are the state, control and disturbance vectors and \mathbf{A} , \mathbf{B} and γ are respectively system state matrix, control input matrix and disturbance input matrix of appropriate dimensions.

$$\mathbf{X} = \begin{bmatrix} \int ACE_1 & \int ACE_2 & \Delta F_1 & \Delta P_{g11} & \Delta X'_{e11} & \Delta P_{g12} & \Delta P'_{g12} & \Delta X'_{e12} & \Delta P_{tie12} \\ \Delta F_2 & \Delta P_{g21} & \Delta X'_{e21} & \Delta P_{g22} & \Delta P'_{g22} & \Delta X'_{e22} & \Delta E_{d1} & \Delta I_{d1} & \Delta E_{d2} & \Delta I_{d2} \end{bmatrix}^T \quad (7)$$

$$\mathbf{U} = \begin{bmatrix} \Delta P_{C1} & \Delta P_{C2} \end{bmatrix}^T \quad (8)$$

$$\mathbf{D} = \begin{bmatrix} \Delta P_{L1} & \Delta P_{L2} & \Delta P_{L3} & \Delta P_{L4} & \Delta P_{uc1} & \Delta P_{uc2} \end{bmatrix}^T \quad (9)$$

The state variables ΔE_{d1} , ΔE_{d2} , ΔI_{d1} and ΔI_{d2} for the SMES unit are integrated into the state equation of the power system model as given in (7). The objective is to obtain the optimum values of the controller parameters which will minimize this objective function or the performance index, J [13].

$$J = \int \left(\Delta F_i^2 + \Delta P_{tie1-2}^2 \right) dt \quad (10)$$

Optimal PI Gain Using ACS Algorithm

Artificial Cooperative Search algorithm (ACS) [12] is a swarm intelligence algorithm developed for solving real valued numerical optimization problems. ACS algorithm is applied for optimizing the proportional integral controller gains for a two area interconnected thermal power system with GDB nonlinearity and SMES units in deregulated environment. The general description of ACS algorithm is explained below followed by the implementation of ACS algorithm for optimal PI gain tuning for the proposed de-regulated power system. The swarm intelligence philosophy behind ACS algorithm is based on the migration of two artificial super organisms as they biologically interact to achieve the global minimum value pertaining to the problem. A mutualism based biological interaction exists between different living species in nature. The living species involved in a mutualism based biological interaction try to derive mutual benefits from the mentioned interaction. Cooperation is the interaction of homogenous living species that adopt mutualism. Mutualism and cooperation based biological in-teraction of two eusocial superorganisms living in the same environment inspired the ACS algorithm. The habitat concept in ACS algorithm matches the search space concept that belongs to the related problem.

In ACS algorithm, a superorganism consisting of random solutions of the related problem corresponds to an artificial superorganism migrating to more productive feeding areas. ACS algorithm contains two superorganisms; α and β that have artificial sub-superorganisms equal to the dimension of the population (N). The dimension of the problem (D) is equal to the number of individuals within the related sub-superorganisms. In ACS algorithm, α and β superorganisms are used for the detection of artificial Predator and Prey sub-superorganisms. The Predator sub-superorganisms in ACS algorithm can pursue the Prey sub-superorganisms for a period of time while they migrate towards global minimum of the problem. When the iterative calculation process of ACS algorithm that is named as co evolution process is considered, it can be seen that the two superorganisms looking for the global minimum of the related problem, establish cooperation based biological interaction between each other. In ACS algorithm the initial values of the individuals of ith sub-superorganism of α (i.e., $\alpha_{(i,j)}$) and β (i.e., $\beta_{(i,j)}$) are defined by using (11) and (12);

$$\alpha_{i,j,g=0} = \text{rand.}(\text{up}_j - \text{low}_j) + \text{low}_j \tag{11}$$

$$\beta_{i,j,g=0} = \text{rand.}(\text{up}_j - \text{low}_j) + \text{low}_j \tag{12}$$

where $i = 1, 2, 3, \dots, N$, $j = 1, 2, 3, \dots, D$ and $g = 0, 1, 2, 3, \dots, \text{max cycle}$. The ‘g’ value here denotes the generation number expressing the co evolution level containing the related superorganisms. The rand shows a random number chosen from the uniform distribution with $U \sim [0, 1]$. The up_j and low_j are the upper and lower limits of search space for jth dimension of the related problem. The productivity values (i.e., fitness values) obtained by the related sub-superorganisms are computed by using (13) and (14);

$$y_{i;\alpha} = f(\alpha_i) \tag{13}$$

$$y_i; \beta = f(\alpha_i) \quad (14)$$

The biological interaction location, X , between Predator and Prey sub-superorganisms is modelled using the equation (15);

$$X = \text{Predator} + R(\text{Prey} - \text{Predator}) \quad (15)$$

Where, R is the Scale factor that controls the speed of biological interaction. The probabilistic nature of ACS algorithm causes the super-organism that is determined as the predator to be changed in each generation. Therefore, ACS algorithm provides a cooperative/co-evolution process for both of the superorganisms. The pseudo code of ACS algorithm is provided in [12]. The proposed algorithm can be implemented with convergence, iteration or tolerance as the stopping criteria. In this proposed study, iteration count has been taken as the stopping criteria.

For LFC in a deregulated environment using ACS algorithm, initially the random generated biological interaction location X , here in our problem it denotes the controller parameters K_p and K_i , which is used to calculate fitness value J . For each iteration, the sub-superorganism (α and β) values are obtained using (10) and (11). The predator and prey sub-superorganisms are determined in each generation by using α and β superorganisms. The biological interaction location X , between predator and prey is updated using (14). The objective function J is calculated for each set of X using (15). ACS algorithm provides a cooperative / co- evolution process for both the superorganisms. The process is repeated until optimum gains, optimal K_p and K_i , corresponding to global minimum objective function value is obtained. Iteration count is taken as the stopping criteria.

Simulation Results

An interconnected two-area system thermal power system having one reheat turbine and one non-reheat turbine with GDB nonlinearity and SMES unit in each area in the deregulated environment as shown in Figure.1 is used to demonstrate the effectiveness of SMES unit and the proposed artificial cooperative search algorithm.

Table 1: Optimal Gain Values

Type of PI controller	Feedback gains	Cost function value
Controller designed using ISE criterion	$K_p = 1.5050$ $K_i = 0.3300$	391.2692
Controller designed using ACS Algorithm	$K_p = 0.0027$ $K_i = 1.0925$	181.5486

Table 1 shows the optimal PI controller gain values and the corresponding cost function values for ACS algorithm designed controller and conventional controller. In this scenario-1 of case study, the participation of all GENCOs is equally distributed in LFC operation. The area participation factors are $apf_1=apf_2=apf_3=apf_4= 0.5$. The load

changes are assumed to occur only in area 1, so the load is demanded by DISCO 1 and DISCO 2. The PU load of DISCO 1 and DISCO 2 are assumed as 0.1pu MW. Therefore the entries in DPM becomes as given below

$$DPM = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

The generation of GENCO (ΔP_{Mi}) is expressed in terms of contract participation factor (cpf) and load demand of DISCOs (ΔP_{Lj}) as given below

$$\Delta P_{Mi} = \sum_j cpf_{ij} \Delta P_{Lj} \tag{16}$$

$$\Delta P_{M1} = cpf_{i1} \Delta P_{L1} + cpf_{i2} \Delta P_{L2} + cpf_{i3} \Delta P_{L3} + cpf_{i4} \Delta P_{L4}$$

For this test case

$$\Delta P_{M1} = (0.5 \times 0.1) + (0.5 \times 0.1) + 0 + 0 = 0.1 \text{ p.u MW}$$

$$\Delta P_{M2} = (0.5 \times 0.1) + (0.5 \times 0.1) + 0 + 0 = 0.1 \text{ p.u MW}$$

$$\Delta P_{M3} = 0 + 0 + 0 + 0 = 0 \text{ p.u MW}$$

$$\Delta P_{M4} = 0 + 0 + 0 + 0 = 0 \text{ p.u MW}$$

Frequency responses of the interconnected multi-area deregulated power system for POOLCO scenario are shown in Figures.4-10. For comparison sake, the responses of conventional PI controller are also shown.

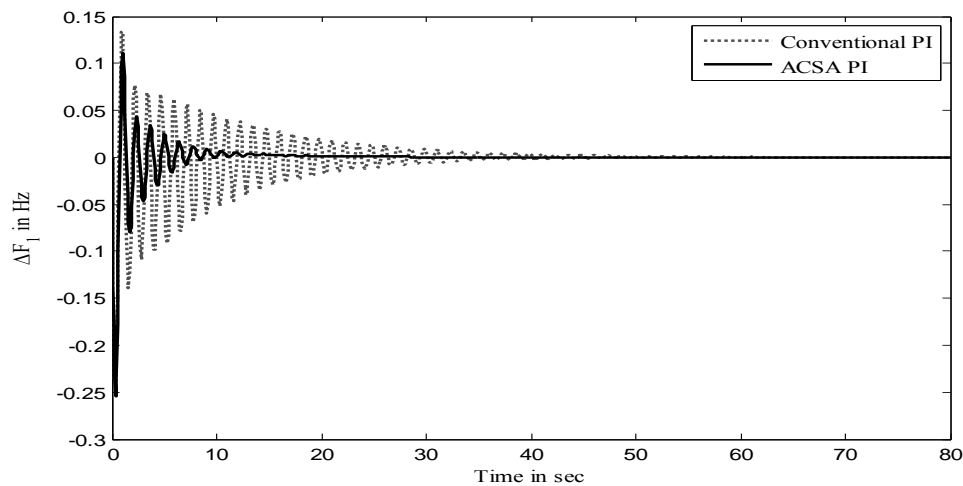


Figure 4: Frequency deviations of area 1

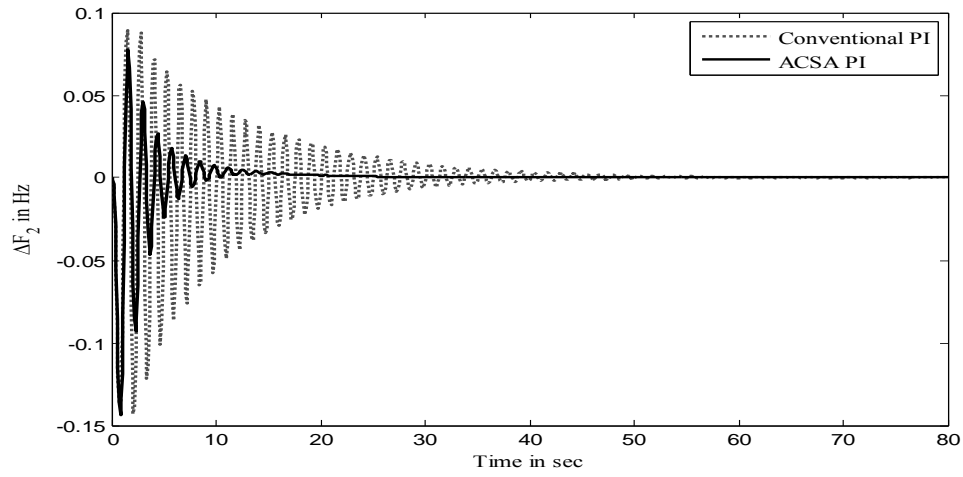


Figure 5: Frequency deviation of area 2

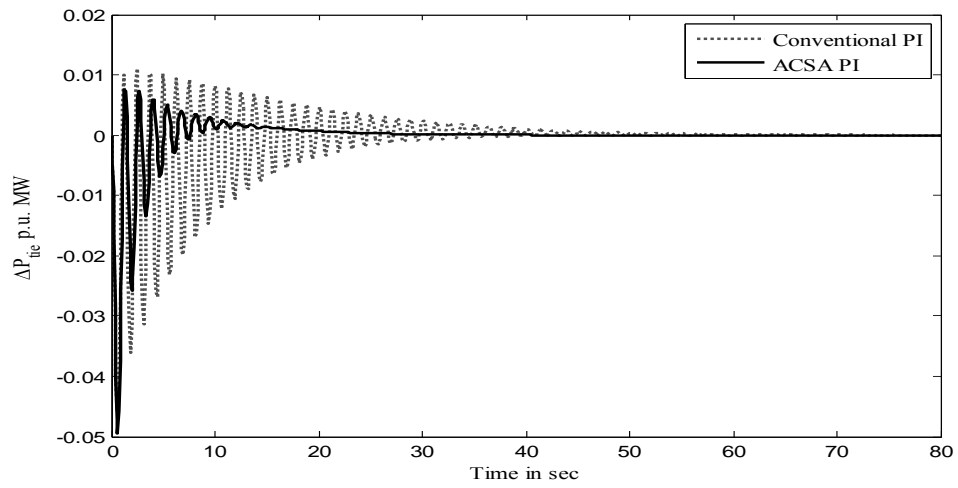


Figure 6: Change in tie line power

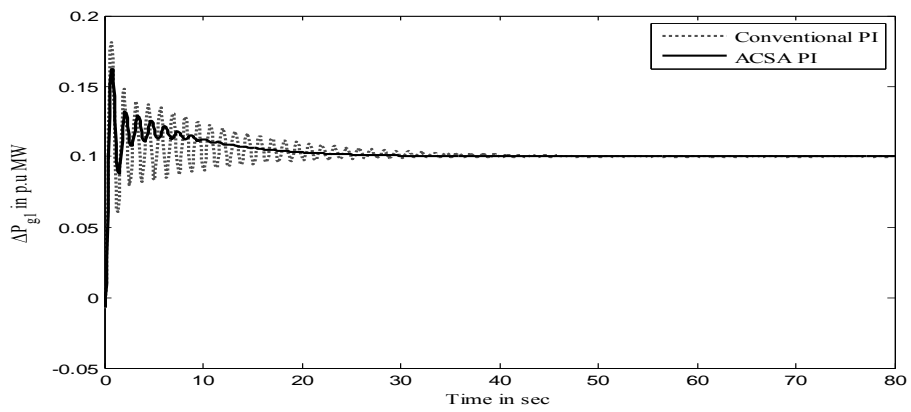


Figure 7: Generated power of GENCO 1

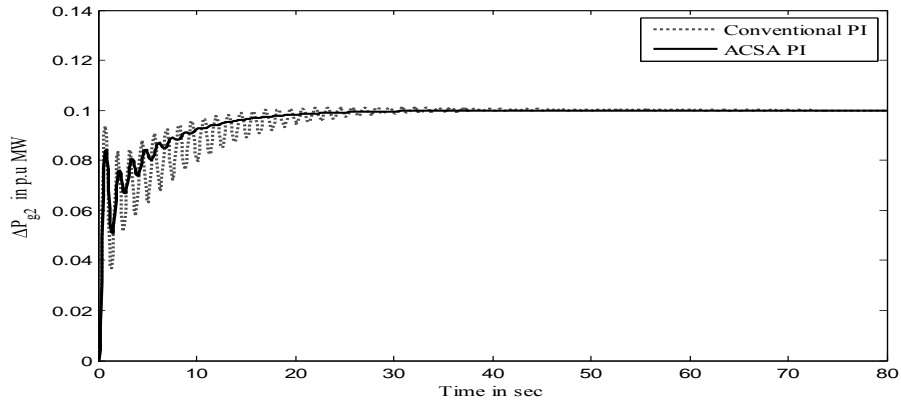


Figure 8: Generated power of GENCO 2

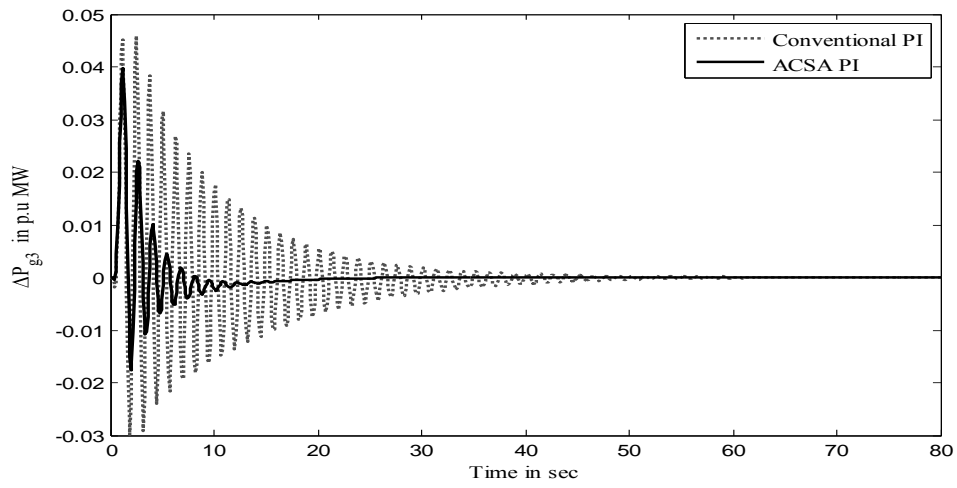


Figure 9: Generated power of GENCO 3

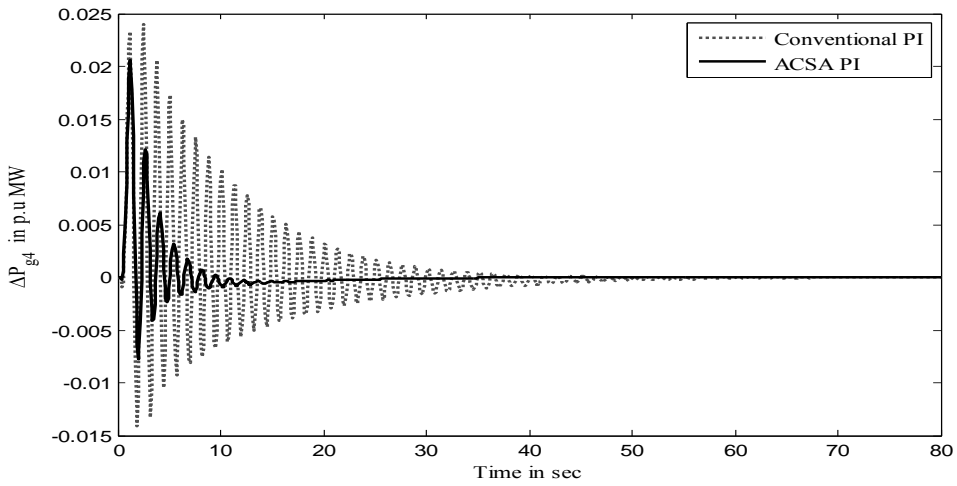


Figure 10: Generated power of GENCO 4

It is observed that the frequency deviation of each area and the tie-line power deviations have a good dynamic response with SMES unit and controller designed using ACS algorithm. It has also been observed that during steady state, the generations of GENCOs are at their desired values.

In the scenario-2 of case study, the DISCOs have a contract with any GENCO in any other area as per the DPM. The area participation factors are $apf_1 = 0.75$, $apf_2 = 0.25$, $apf_3 = 0.5$, $apf_4 = 0.5$. Each DISCO demands 0.1 p.u MW power from GENCOs. Therefore the entries in DPM becomes as given below

$$DPM = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix}$$

The scheduled tie line power from area 1 to area 2 is calculated from the off diagonal blocks of the DPM using the following expression,

$$\Delta P_{\text{tie scheduled}} = \sum_{i=1}^2 \sum_{j=3}^4 cpf_{ij} \Delta P_{Lj} - \sum_{i=3}^4 \sum_{j=1}^2 cpf_{ij} \Delta P_{Lj} \quad (17)$$

$$\begin{aligned} &= (cpf_{13} + cpf_{23}) \Delta P_{L3} + (cpf_{14} + cpf_{24}) \Delta P_{L4} - (cpf_{31} + cpf_{41}) \Delta P_{L1} - (cpf_{32} + cpf_{42}) \Delta P_{L2} \\ &= (0+0)0.1 + (0.3+0)0.1 - (0+0.3)0.1 - (0.25+0.25)0.1 \\ &= -0.05 \text{ p.u MW.} \end{aligned}$$

The generation of GENCO (ΔP_{Mi}) is calculated using (16) as follows,

$$\begin{aligned} \Delta P_{M1} &= (0.5 \times 0.1) + (0.25 \times 0.1) + 0 + (0.3 \times 0.1) \\ &= 0.105 \text{ p.u MW} \end{aligned}$$

$$\begin{aligned} \Delta P_{M2} &= (0.2 \times 0.1) + (0.25 \times 0.1) + 0 + 0 \\ &= 0.045 \text{ p.u MW} \end{aligned}$$

$$\begin{aligned} \Delta P_{M3} &= (0 \times 0.1) + (0.25 \times 0.1) + (1 \times 0.1) + (0.7 \times 0.1) \\ &= 0.195 \text{ p.u MW} \end{aligned}$$

$$\begin{aligned} \Delta P_{M4} &= (0.3 \times 0.1) + (0.25 \times 0.1) + 0 + 0 \\ &= 0.055 \text{ p.u MW} \end{aligned}$$

Figure.11 and Figure.12 show the frequency deviation in both the areas. Figure.13 shows the tie-line power deviation. The frequency deviations and tie line power deviations have been reduced effectively by using the SMES unit and ACS algorithm designed controller. Figure.14 shows the scheduled tie-line power flow which settles at -0.05 pu MW. Figures.15-18 shows the generated powers of GENCOs. It is observed that the generations are at their desired levels during the steady state

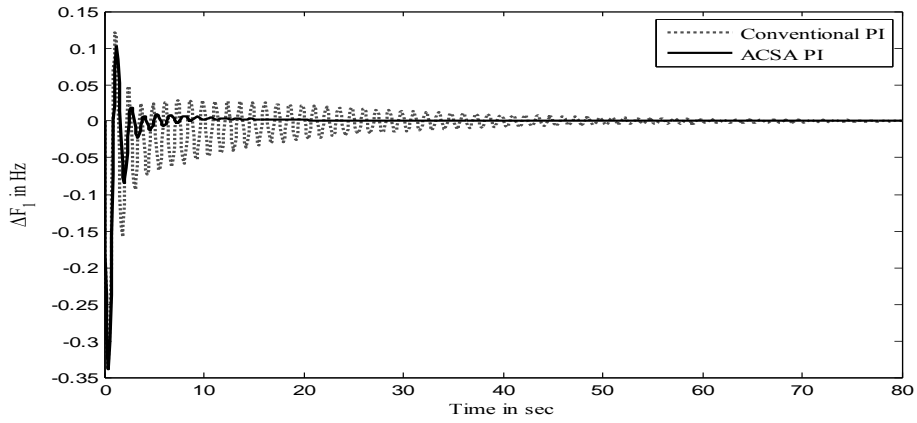


Figure 11: Frequency deviations of area 1

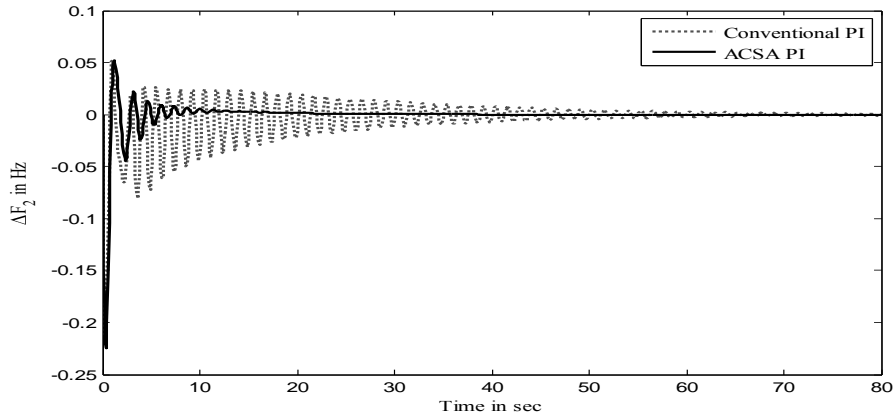


Figure 12: Frequency deviations of area 2

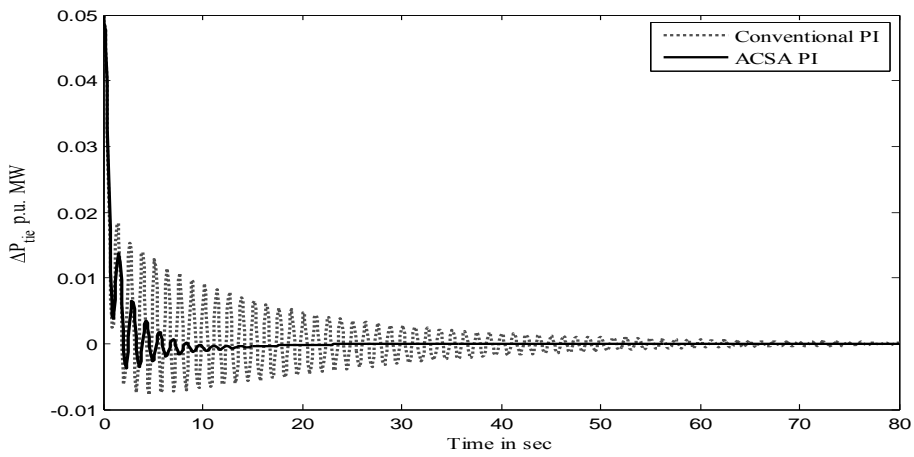


Figure 13: Change in tie line power

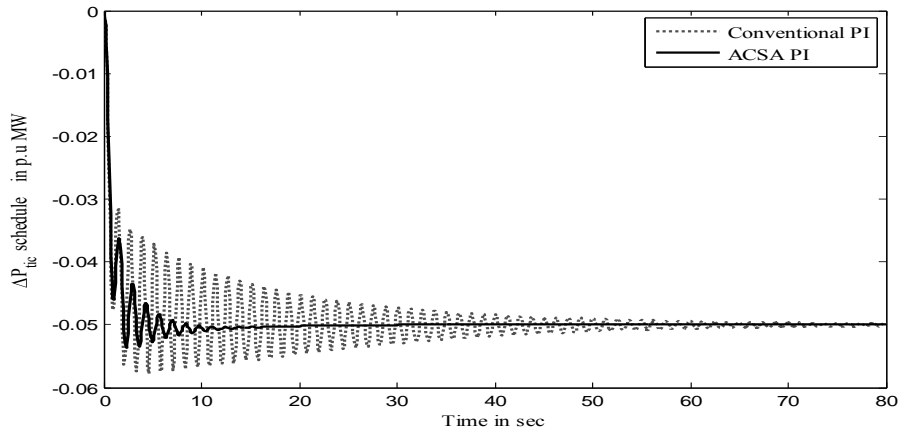


Figure 14: Scheduled tie line power

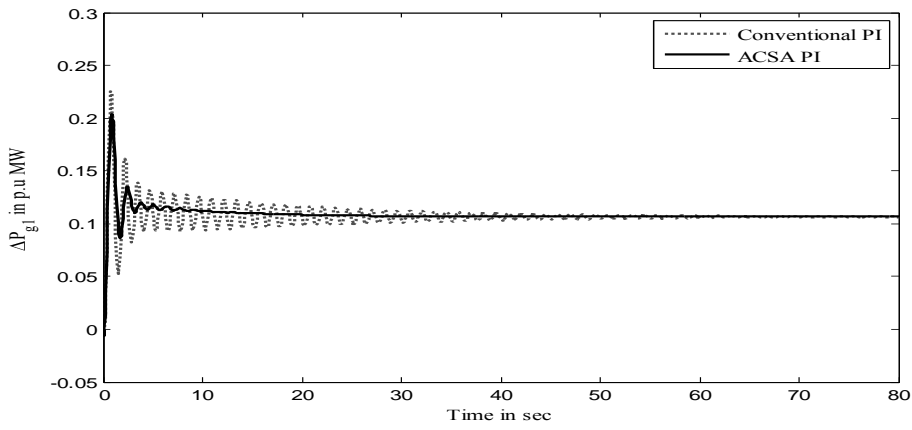


Figure 15: Generated power of GENCO 1

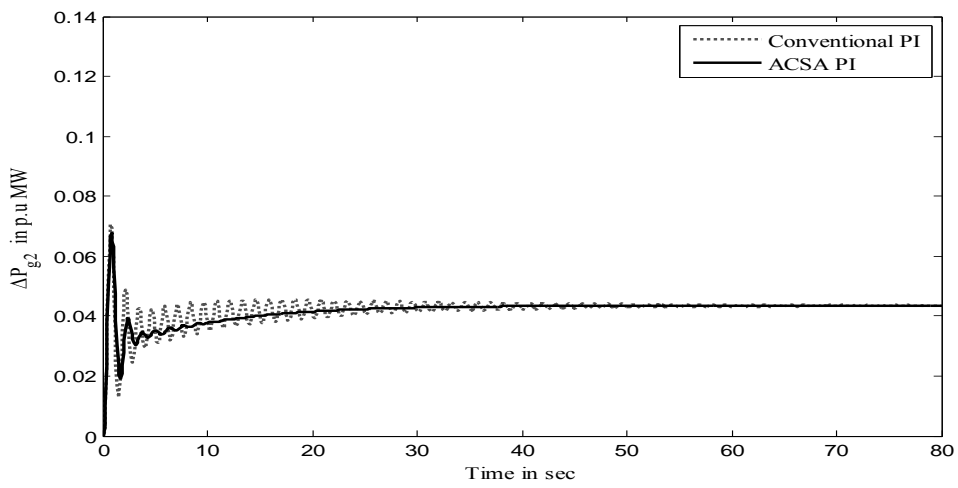


Figure 16: Generated power of GENCO 2

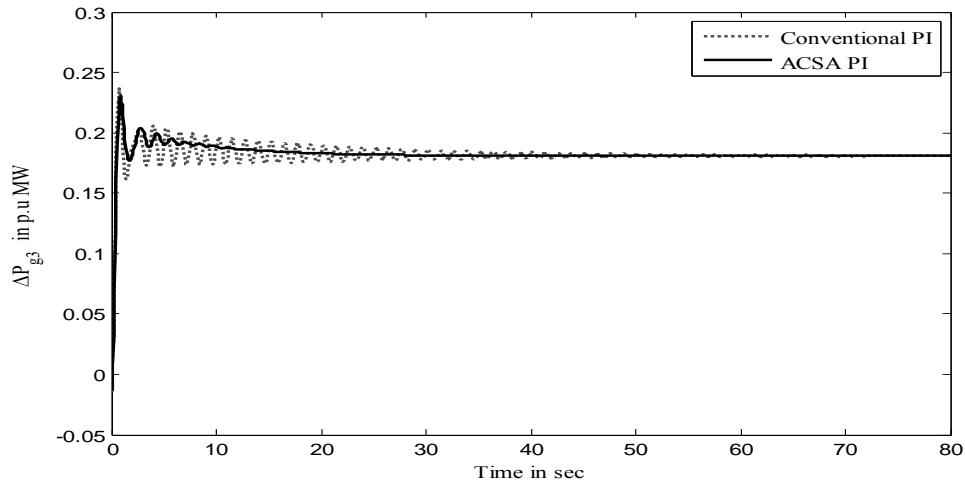


Figure 17: Generated power of GENCO 3

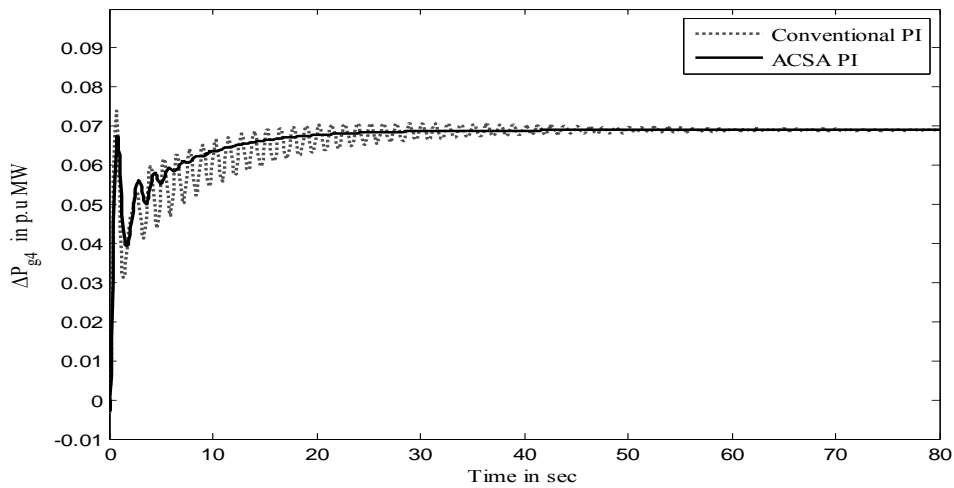


Figure 18: Generated power of GENCO 4

In this scenario-3, the violation of contract happens as DISCO 1 demands 0.1 pu MW more power than its contracted power. The uncontracted power will be supplied by the GENCOs present in the same area of the DISCO which violates the contract. The total load in area 1 is equal to the load of DISCO 1, load of DISCO 2 and the uncontracted load, which is equal to 0.3 pu MW. Similarly, the load in area 2 is equal to the sum of the loads of DISCO 3 and DISCO 4 which is 0.2 pu MW. The DPM is same as in scenario 2.

From the simulation results show in Figures.19-26, it has been observed that the Generation of GENCO 1 and GENCO 2 are affected by the uncontracted load of DISCO 1, whereas the generation of GENCO 3 and GENCO 4 remain unaltered due to the uncontracted load. The uncontracted load demand is met by the GENCOs in area 1. The frequency deviations and tie-line power deviations are reduced effectively

using ACS designed PI controller. It is also observed that the generations are at their scheduled levels during the steady state operation.

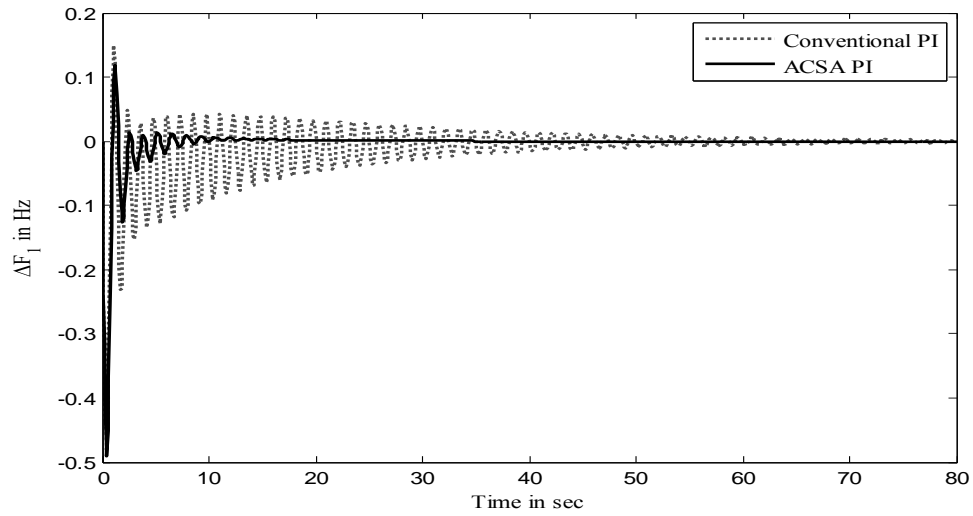


Figure 19: Frequency deviation of area 1

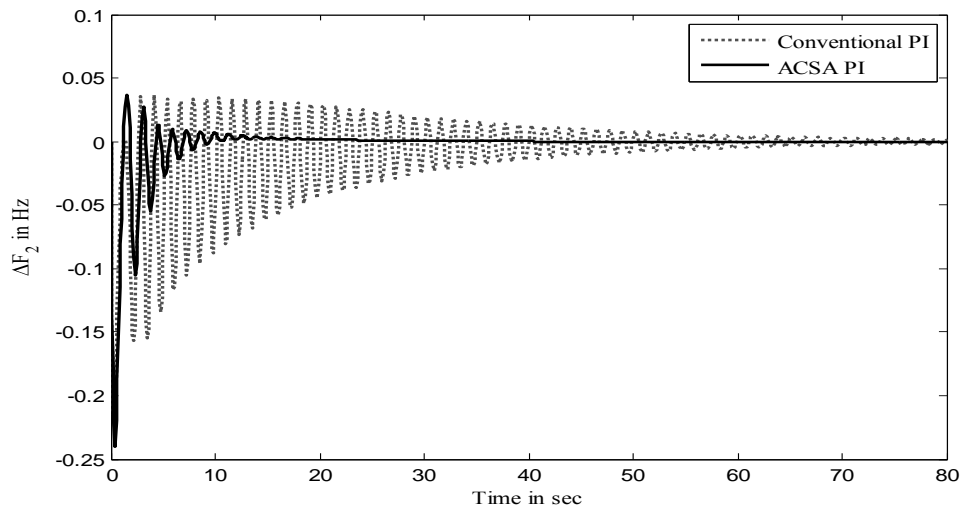


Figure 20: Frequency deviation of area 2

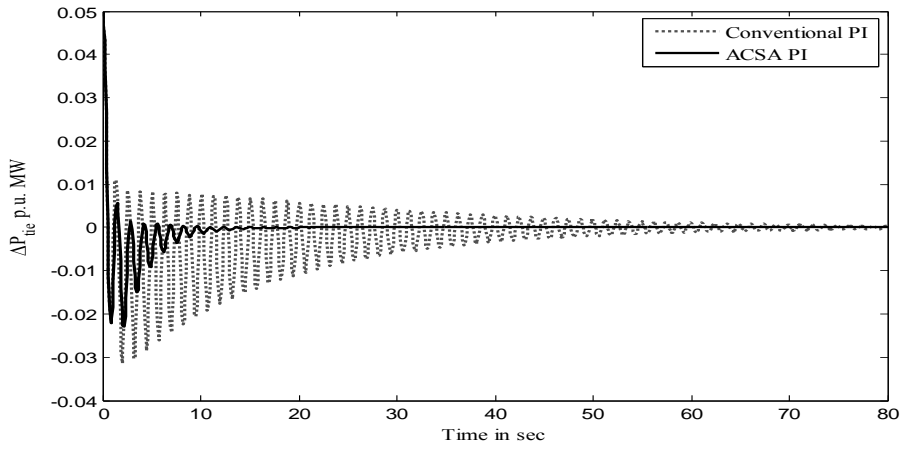


Figure 21: Change in tie line power

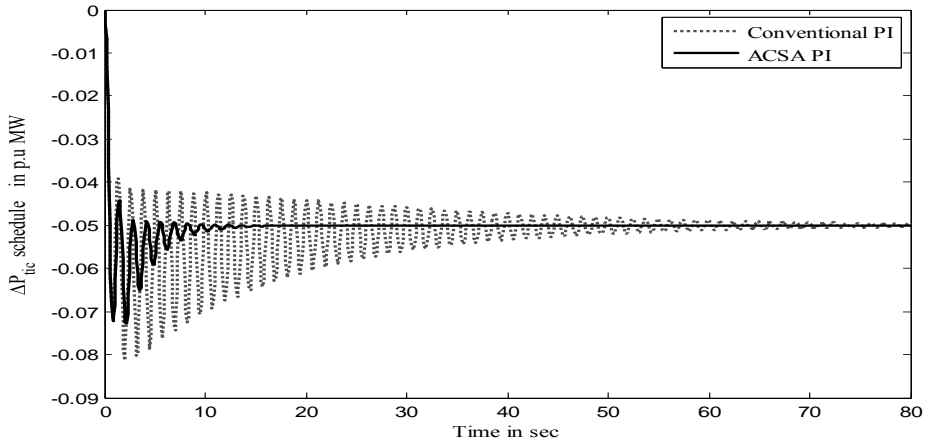


Figure 22: Scheduled tie line power

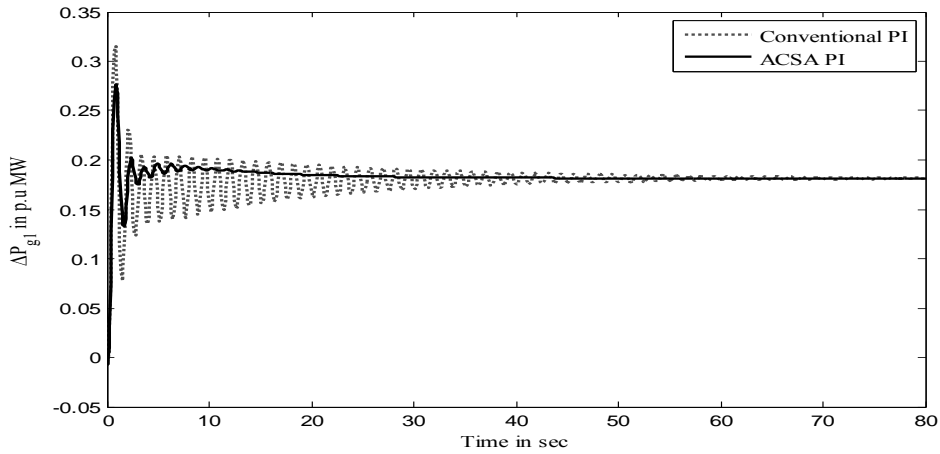


Figure 23: Generated power of GENCO 1

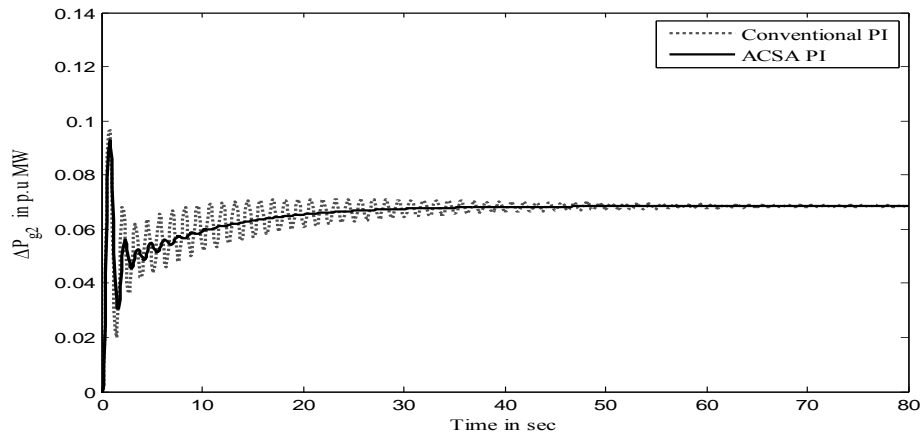


Figure 24: Generated power of GENCO 2

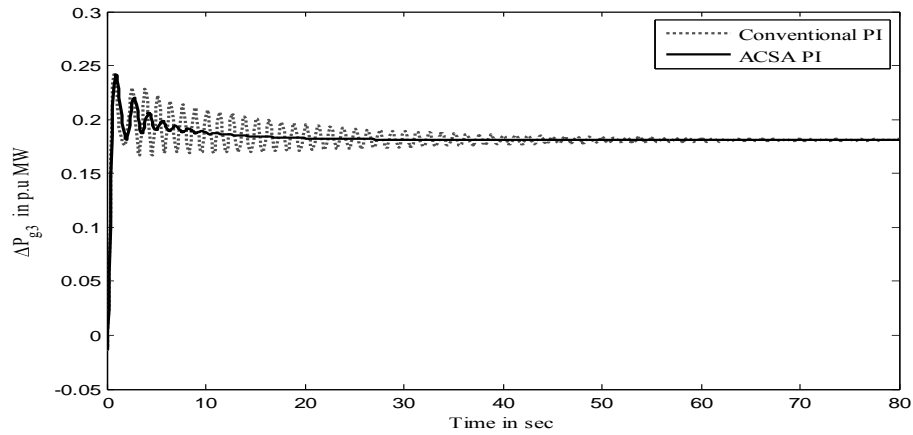


Figure 25: Generated power of GENCO 3

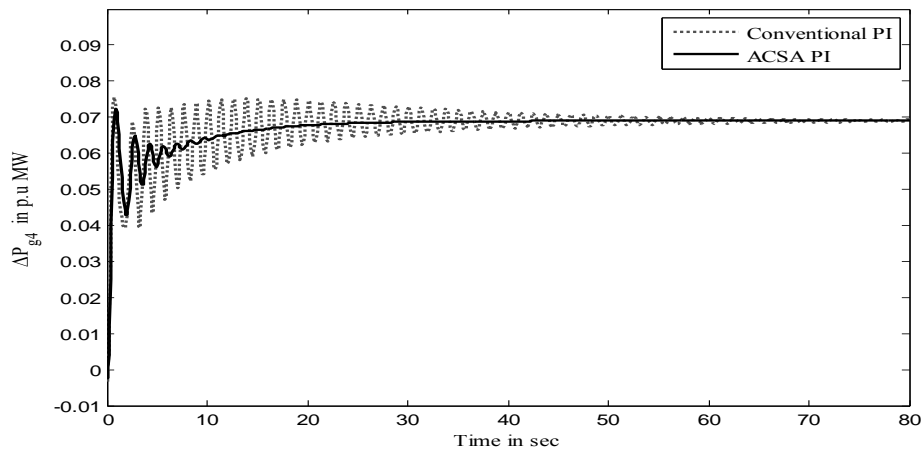


Figure 26: Generated power of GENCO 4

Conclusion

A design of Artificial Cooperative Search algorithm based load frequency controller for multi-area interconnected deregulated thermal power system with SMES and GDB nonlinearity is presented. The proposed ACS algorithm based controller design has been successfully applied to an interconnected two area thermal deregulated power system with two thermal generating units and with SMES unit and Governor dead band in each area. It has been found that the addition of Super Conducting Magnetic Energy Storage units in both areas of the power system has significantly improved the system responses and the oscillations are suppressed effectively in deregulated environment. The SIMULINK\ MATLAB results reveal that the Super Conducting Magnetic Energy Storage (SMES) units along with ACS algorithm designed controller ensures effective attenuation of frequency and tie-line power deviations to zero even in the presence of GDB nonlinearity under various bilateral contracts. It has also been observed that the generations are at their desired levels during the steady state.

Appendix

Data for the two-area interconnected thermal power system [5] and [9] .

Rating of each area = 2000 MW, Base power = 2000 MVA, $f^{\circ} = 60$ Hz, $R_{11} = R_{12} = R_{21} = R_{22} = 2.4$ Hz/p.u.Hz, $T_{g11} = T_{g12} = T_{g21} = T_{g22} = 0.08$ s, $T_{t11} = T_{t12} = T_{t21} = T_{t22} = 0.3$ s, $T_{r12} = T_{r22} = 10$ s, $K_{ps1} = K_{ps2} = 120$ Hz/p.u.MW, $K_{r12} = K_{r22} = 0.5$, $T_{ps1} = T_{ps2} = 20$ s, $\beta_1 = \beta_2 = 0.425$ p.u. MW/Hz, $2\pi T_{12} = 0.545$ p.u.MW/Hz, $N_1 = 0.8$, $N_2 = -0.2/\pi$.

SMES data: $K_{01} = K_{02} = 50$ kV/unit ACE, $I_{d1,2min} = 4.05$ kA, $I_{d1,2max} = 6.21$ kA, $I_{do} = 5$ kA, $L = 2$ H, $K_{id1} = K_{id2} = 0.20$ kV/kA

References

- [1]. Rakhshani.E and Sadeh.J, 2008. Load Frequency Control of Multi-Area Restructured Power System. Power System Technology and IEEE Power India Conference. IEEE, New Delhi, INDIA, pp.1-7.
- [2]. Ganapathy.S and Velusami.S, 2010. MOEA Based Design of Decentralized Controllers for LFC of Interconnected Power Systems with nonlinearities, AC-DC parallel tie-lines and SMES units. Energy Conversion and Management. Vol. 51, pp. 873-880.
- [3]. Abraham R.J, Das.D and Patra.A, 2007. Automatic generation control of an interconnected hydrothermal power system considering Super Conducting Magnetic Energy Storage, Electrical Power Energy Systems. 29 (8): pp. 571-579.
- [4]. Tripathy S.C, Hopes G.S and Malik O.P, 1982. Optimizations of load-frequency control parameters for power systems with reheat steam turbines and governor dead band nonlinearity, IEE Proceedings. 129(1): pp. 10-11.
- [5]. Ganapathy.S and Velusami.S, 2009. Design of MOEA Based Decentralized Load Frequency Controllers for Interconnected Power

- Systems with GDB nonlinearity, *Journal of electrical engineering*. 9 (4): pp. 47-52.
- [6]. Singh.O, Tiwari.P, Ibraheem et al., 2013. A Survey of Recent Automatic Generation Control Strategies in Power Systems, *International Journal of Emerging Trends in Electrical and Electronics*. 7 (2):pp. 1-14
 - [7]. Sathans and Swarup.A, 2011. Intelligent Load Frequency Control of Two-Area Interconnected Power System and Comparative Analysis, *International conference on Communication Systems and Network Technologies*. IEEE, Katra, Jammu, INDIA, pp.360-365.
 - [8]. Bekhouche.N, 2002. Automatic Generation Control before and After Deregulation, *Thirty-Fourth Southeastern Symposium on System Theory*, IEEE, Huntsville, Alabama, USA, pp.321-323.
 - [9]. Donde.V, Pai.M.A and Hiskens I.A, 2001. Simulation and optimization in a LFC system after deregulation. *IEEE Transactions on Power Systems*, 16 (3): pp. 481-489.
 - [10]. Tripathy S.C, Balasubramanian.R and Chandramohanan Nair P.S, 1992. Adaptive Automatic Generation Control with Superconducting Magnetic Energy Storage in Power Systems, *IEEE Transactions on Energy Conversion*. 7(3): pp. 434-441.
 - [11]. Demiroren and Yesil.E, 2004. Automatic generation control with fuzzy logic controllers in the power system including SMES units, *Electric Power and Energy Systems*. 26 (4): pp. 291-305.
 - [12]. Civicioglu.P, 2013. Artificial cooperative search algorithm for numerical optimization problems, *Information Sciences*. 229: pp. 58-76.
 - [13]. Parida.M and Nanda.J, 2005. Automatic Generation Control of a Hydro-Thermal System in Deregulated Environment, *Proceedings of the Eighth International Conference on Electrical machine systems*. IEEE, Nanjing, CHINA. pp. 942-947.