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ARTIFICIAL COOPERATIVE SEARCH ALGORITHM BASED LOAD FREQUENCY CONTROLLER FOR MULTI-AREA DEREGULATED POWER SYSTEM WITH COORDINATED CONTROLOF TCPS, RFB AND AC-DC PARALLEL TIE-LINES

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ABSTRACT

This paper presents the design and analysis of Artificial Cooperative Search (ACS) algorithm based Load Frequency Controller with the presence of Thyristor Controlled Phase Shifter (TCPS), Redox Flow Battery (RFB) and AC-DC parallel tie-lines for interconnected deregulated power system. In deregulated power scenario, specialized agencies for generation, transmission and distribution have been formed for increasing the reliability and efficiency of power system operation. This effects the formulation of LFC problem, so the traditional LFC model is modified to consider the bilateral contracts in the deregulated environment. The deviations in frequency and interarea tie-line power from their prescribed values following a load disturbance are of great concern in power system operation and control. It is possible to effectively suppress the frequency and tie-line power deviations by coordinated control of TCPS and RFB with AC-DC parallel tie-lines for different operating scenarios in deregulated environment. The simulation results reveal the superior performance of Artificial Cooperative Search (ACS) algorithm tuned Load Frequency Controller.

Keywords: artificial cooperative search algorithm, AC-DC parallel tie-lines, deregulated power system, load frequency control, redox flow battery, thyristor controlled phase shifter.

INTRODUCTION

In the past decade, the drift towards deregulation of power system has increased progressively throughout the world. In the deregulated power set-up, different utilities for generation (GENCO), transmission (TRANSCO) and distribution (DISCO) have been shaped to enhance the trustworthiness and competence of power system. An Independent System Operator (ISO) monitors the process of GENCO, TRANSCO and DISCO based on the mutual contracts of deregulated power system [1]. Investigation of global power system markets reveals that Load Frequency Control is a major supplementary service in deregulated service [2]. The objectives of LFC to sustain the reliability of power system at tolerable level still continue unchanged. A variety of control aspects linking to the LFC problem have been highlighted in [3].

Modern power systems are outsized, composite and interrelated, having various uncertainties and a variety of disturbances. Power system frequency is one of the most significant factor which is related to the safety, stability and efficiency of the power system. For successful operation of power system, matching of active power with the total load demand is of atmost importance. LFC is an important aspect in power system operation and control for maintaining the power system frequency and tie-line power flows within the scheduled limits.

Several authors have studied and proposed different controllers for LFC operations [4]. Most of these controllers are based on the traditional approach which are tuned on trial and error approach and requires more time and human expertise for tuning. To overcome these drawbacks, several artificial intelligent techniques have been proposed in literature [5, 6]. Artificial Cooperative Search algorithm based Load Frequency Controller has been proposed in this paper. ACS is a swarm intelligence algorithm formulated for solving complex numerical optimization problems. The viewpoint behind ACS algorithm is based on the migration of two artificial superorganisms as they biologically cooperate to attain the global minimum value pertaining to the problem. ACS algorithm is simple, easy to implement and efficient for solving complex numerical optimization problems [7].

In modern days, the use of fast reacting power electronic devices in power system operation and control has been on the increase. The FACTS devices provide more flexibility in power system operation and control [8]. A Thyristor Controlled Phase Shifter (TCPS) is likely to be a well-organized device for inter-area tie-line power flow control of an interconnected power system. The TCPS is installed in series with AC tie-line between two areas and has the ability to manage the system frequency optimistically through interconnection. By controlling the phase angle of TCPS, the tie-line power flow can be controlled in an effective manner [9]. During a small load interruption and with the optimal gain values for the PI controller, the frequency deviations and tie-line power deviations continue for an extended period. During such circumstances, the governor system may no longer be able to take up the frequency deviations due to its slow nature.

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Thus, to compensate for the unexpected load changes, an active power source with fast comeback is likely to be the most successful counter measure. With exceptional short-time overload output and response characteristics possessed by Redox Flow batteries in particular, the effects of generation control and of the absorption of power variation desired for power quality are well met out [10].

The major attention in HVDC transmission system is for the reason of its cost-effective, ecological and performance advantages over other alternatives. Because of the distinctive advantages of HVDC transmission system, it has been functional widely in operating a DC link in parallel with an AC link inter-connecting control regions to get an enhanced system active performance [11, 12]. In this paper, the design and analysis of ACS algorithm based Load Frequency Controller with coordinated control of TCPS, RFB and AC-DC parallel tie-lines for interconnected deregulated power system has been proposed. The simulations results make known the effectiveness of the projected ACS tuned LFC controller in deregulated atmosphere.

Deregulated LFC power system model

To progress the effectiveness of operation of the existing power system scenario, deregulation standards have been introduced into the existing power system configuration. In deregulated atmosphere, the GENCOs and DISCOs can have a variety of mutual contracts in-between themselves. The DISCO Participation Matrix (DPM) can be used to understand the mutual contracts among various GENCOs and DISCOs. The particulars of the contracts among 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 [13].

$$\Sigma_i \mathrm{cpf}_{ij} = 1 \quad (1)$$

The projected deregulated power system is a two-area thermal power system with TCPS, RFB and AC-DC parallel tie-lines in deregulated scenario as shown in Figure-1. The corresponding DPM matrix is as given below, where cpf represents the contract participation factor.

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

The off diagonal entries in the DPM represent the demand of DISCO in one area with the GENCO in another area. The change in load demand of DISCO is reflected as a local load in the area at which the DISCO is present.

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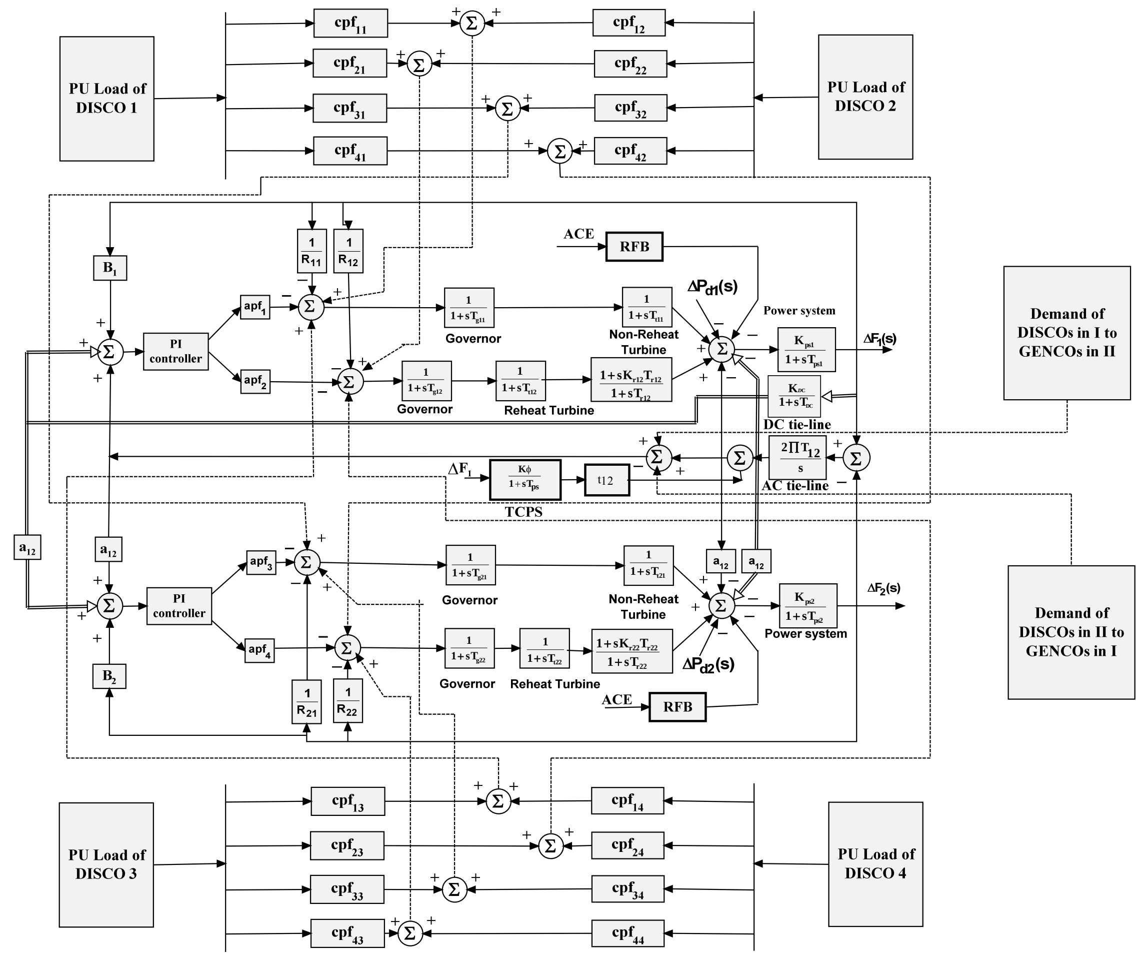

Figure-1.LFC model in deregulated power scenario.

The scheduled tie-line power flow is given by

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

The error in tie-line power signal is calculated as given by

$$\Delta P_{\text{tie error}} = \Delta P_{\text{tie actual}} - \Delta P_{\text{tie scheduled}} \qquad (3)$$

The tie-line error signal becomes zero during the steady state operation. The tie-line error signal is used to generate the area control error signal [13].

Thyristor Controlled Phase Shifter (TCPS)

A thyristor controlled phase shifter (TCPS) is a successful power electronic device for the tie-line power flow control of an interconnected power system.TCPS is a device that changes the relative phase angle between the system voltages. The tie-line power flow can be regulated by controlling the phase angle to damp out the area frequency deviations and improve power system stability. The TCPS is connected in series with the ac tie-line as shown in Figure-2.During a sudden load variation in power system, the TCPS swiftly starts to suppress the transient frequency deviations, then the governor systems takes over the control to compensate for the steady state frequency deviation. The transfer function block diagram of TCPS [14] is shown in Figure-3.

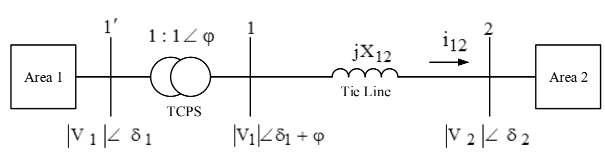

Figure-2. Schematic diagram of TCPS connected in series with the ac tie-line.

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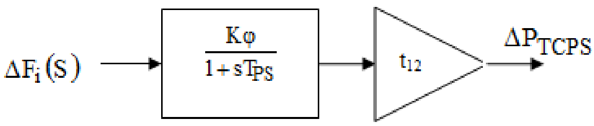

Figure-3. Transfer function block diagram of TCPS.

Redox Flow Battery System (RFB)

Redox Flow Batteries are rechargeable batteries with a tremendous short-time overload output response. RF batteries in practical applications have a number of advantages such as ability to operate at normal temperature, temperature changes are minimum and standby losses are very small. Hence, RFBs have a long service life, flexibility in layout, ease of capacity increase, and free from degradation due to the recurrence of short charge-discharge cycles quick responses. RFBs are not aged by frequent charging and discharging and have outstanding function during overload [10]. Simple operating code, quick response, long service life, suitability for high capacity systems, quick start up and ease in maintenance are the salient features of these batteries which makes it suitable for LFC.When the load demands are low, the RFB charges and the stored energy is delivered back to the system during the peak load demands. The dual converters which are connected with the batteries perform both AC-DC and DC-AC conversions. A simplified transfer function block representation of the RFB [15] is given in the Figure-4. The RF batteries are capable of very fast response and so hunting due to a delay in response will not occur. For this reason, the Area Control Error (ACE) is used as the command value for the RFB in controlling the output response in the LFC problem.

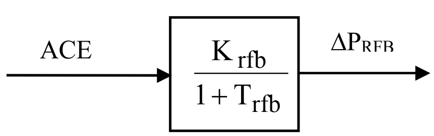

Figure-4. Transfer function block representation of RFB.

AC-DC transmission system

The main attention in HVDC transmission system is because it has economic, environmental and performance advantages over other alternatives. Because of the exceptional advantages of HVDC transmission system, it has been functional broadly in operating a DC link in parallel with an AC link interconnecting control areas to get an enhanced system dynamic performance [11,12]. The HVDC link is connected in parallel with the AC tie-line as shown in Figure-5. The HVDC link consists of mainly a rectifier circuit at one end of the HVDC link and an inverter circuit at the other end of the link. Originally it is assumed that, area-2 initially supplied AC power through AC transmission line to area-1. It is assumed that in area-2 there are sudden large load changes, which causes sudden demand for electric power and serious problem of frequency deviations in area-2. To stabilizing the frequencies deviations in area-2, the required bulk power for effectively damping out the frequency deviations in area-2 is supplied through the HVDC link. The proposed method has large capability of frequency stabilization to other interconnected areas having less capability. The proposed control can serve as a new auxiliary service for stabilizing the deregulated power systems. The transfer function block diagram of HVDC link [16] is given in Figure-5.

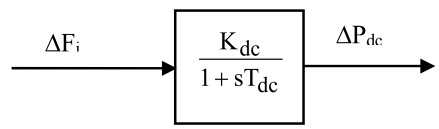

Figure-5. The transfer function block diagram of HVDC link.

Optimal gain tuning using ACS algorithm

Artificial Cooperative Search algorithm (ACS) is a swarm intelligence algorithm developed for solving complex numerical optimization problems [7]. A genetic contact naturally prevails between diverse living things in natural world. The living kind concerned in genetic contact tries to achieve mutual benefits from the natural interaction. The habitation thought in ACS algorithm represents the search space concept that belongs to the associated problem.

In ACS algorithm, a superorganism consisting of arbitrary solutions of the associated problem corresponds to an artificial superorganism migrating to more fruitful 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 associated sub-superorganisms. In ACS algorithm, α and β superorganisms are used for the finding of artificial Predator and Prey sub-superorganisms. The Predator sub-superorganisms in ACS algorithm can follow 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 mutual aid based biological contact between each other. In ACS algorithm, the initial values of the individuals of ith sub-superorganism of α (i.e., α_(i,j)) and β (i.e., β_(i,j)) are defined by using (4) and (5);

$$\alpha_{i,j,g=0} = \mathrm{rand}(up_j - low_j) + low_j \qquad (4)$$

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$$\beta_{i,j,g=0} = \mathrm{rand}(up_j - low_j) + low_j \qquad (5)$$

where i = 1, 2, 3, ... , N, j = 1, 2, 3, ... , D and g = 0, 1, 2, 3, ... , max cycle. The 'g' value denotes the generation number expressing the co-evolution level containing the associated superorganisms. The rand shows a random number chosen from the uniform distribution with U~[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 fitness values are computed by using (6) and (7);

$$y_{i;\alpha} = f(\alpha_i) \qquad (6)$$

$$y_{i;\beta} = f(\beta_i) \qquad (7)$$

The biological interaction location, X, between Predator and Prey sub-superorganisms is modeled using the equation (8);

$$X = \mathrm{Predator} + R(\mathrm{Prey} - \mathrm{Predator}) \qquad (8)$$

Where, R is the scale factor that controls the speed of biological contact. The probabilistic character 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 proposed algorithm has been implemented with iteration count as the stopping criteria. The pseudo code of ACS algorithm is provided in [7].

The proposed deregulated system is a two-area thermal power system with TCPS, RFB and AC-DC tie-lines in deregulated scenario as shown in Figure-1. ACS algorithm is applied for optimizing the proportional plus integral controller gains for a two area interconnected thermal power system in deregulated environment. The LFC model is a two area interconnected power system with one reheat unit and one non-reheat unit in each area. The objective is to obtain the optimum values of the controller parameters which will minimize the performance index or cost function value, J [16].

$$J = \int \left(\Delta F_1^2 + \Delta P_{tie\,1-2}^2 + \Delta P_{dc}^2 \right) dt \qquad (9)$$

For Load Frequency Control in a deregulated environment using ACS algorithm, to begin with, the random generated biological contact position X, i.e. the proportional plus integral controller gain values, are used to calculate fitness value using the cost function, J. For each iteration, the sub-superorganism (α and β) values are obtained using (4) and (5). The predator and prey sub-superorganisms are determined in each generation by using α and β superorganisms. The biological contact position X, between predator and prey is updated using (8). The objective function J is calculated for each set of X using (3). The process is repeated until optimal proportional plus integral gains, corresponding to global minimum cost function value is obtained. Iteration count is taken as the stopping criteria.

SIMULATION RESULTS AND DISCUSSION

An interconnected two-area thermal power system having one reheat turbine and one non-reheat turbine in each area with coordinated control of TCPS, RFB and AC-DC parallel tie-lines in the deregulated environment has been used. ACS algorithm is used to tune the PI controller values for the proposed power system model. Table 1 shows the optimal PI controller gain values obtained using ACS algorithm and their corresponding cost functions. The simulations are performed for different contract scenarios of the deregulated environment. The data required for the simulations are taken from [13 - 16]. To demonstrate the effectiveness of coordinated control of TCPS, RFB and AC-DC parallel tie-lines using ACS algorithm, the simulation has been performed and compared with the simulation results of deregulated power system without coordinated control of TCPS, RFB and AC-DC parallel tie-lines, deregulated power system with coordinated control of TCPS, RFB and AC-DC parallel tie-lines and deregulated power system with coordinated control of TCPS, RFB and AC-DC parallel tie-lines tuned using ACS algorithm.

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Table-1. Optimal proportional plus integral gain values.

Case	Proportional gain	Integral gain	Cost function value
Controller gains without RFB,TCPS and AC-DCtie-lines using ISE criterion	1.14	0.19	159.3813
Controller gains with RFB,TCPS and AC-DC tie-lines using ISE criterion	1.2700	0.7900	106.5566
Controller gains with RFB,TCPS and AC-DCtie-lines using ACS algorithm	0.1117	1.6812	70.1505

Poolco scenario

In the poolco scenario of case study, all the GENCOs have equal participation in LFC operation. The area participation factors are equally assumed as $apf_1 = apf_2 = apf_3 = apf_4 = 0.5$. In this scenario, the load perturbation is 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 Disco Participation Matrix becomes modified 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

$$\Delta P_{Mi} = \sum_j cpf_{ij}\, \Delta P_L \quad (10)$$

The simulation results for this poolco scenario in terms of area frequency deviation and tie-line power flows are shown in Figure-6, Figure-7 and Figure-8.

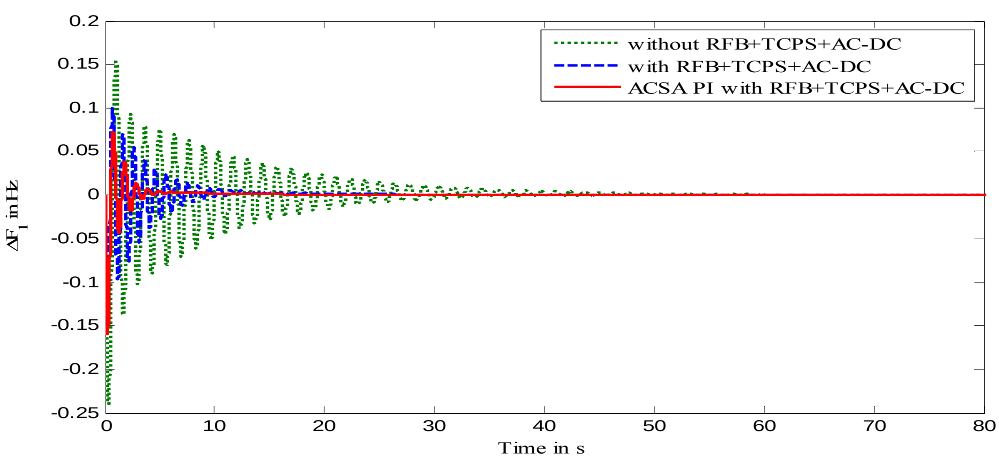

Figure-6. Frequency deviation in area-I.

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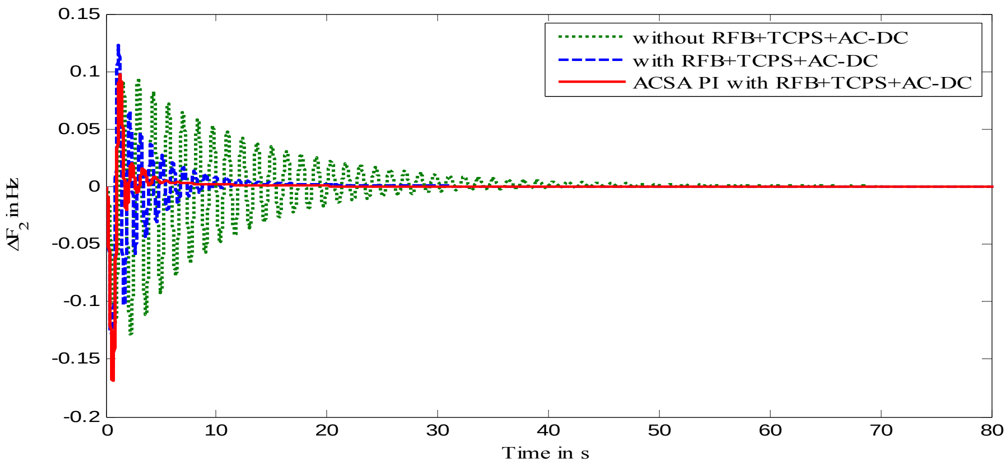

Figure-7. Frequency deviation in area-II.

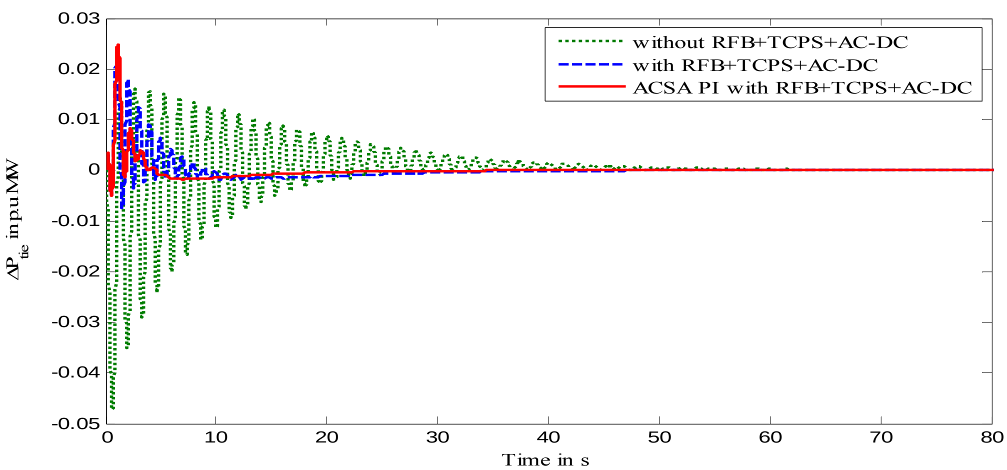

Figure-8. Inter-area tie-line power deviation.

Bilateral contract

In this scenario of case study, all the DISCOs have a contract with any GENCO in any other area as per the DPM. Each DISCO is assumed to demand 0.1p.u MW power from the GENCOs. The area participation factors are $apf_1 = 0.75$, $apf_2 = 0.25$, $apf_3 = 0.5$, $apf_4 = 0.5$. 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 values of the off diagonal elements of the DPM using the following expression,

$$\Delta P_{tiescheduled}=\sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\Delta P_{Lj}-\sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\Delta P_{Lj} \quad (11)$$

The simulation results for the bilateral contract scenario in terms of area frequency deviation and tie-line power flow are shown in Figure-9, Figure-10 and Figure-11. The scheduled tie-line power flow is show in Figure-12.

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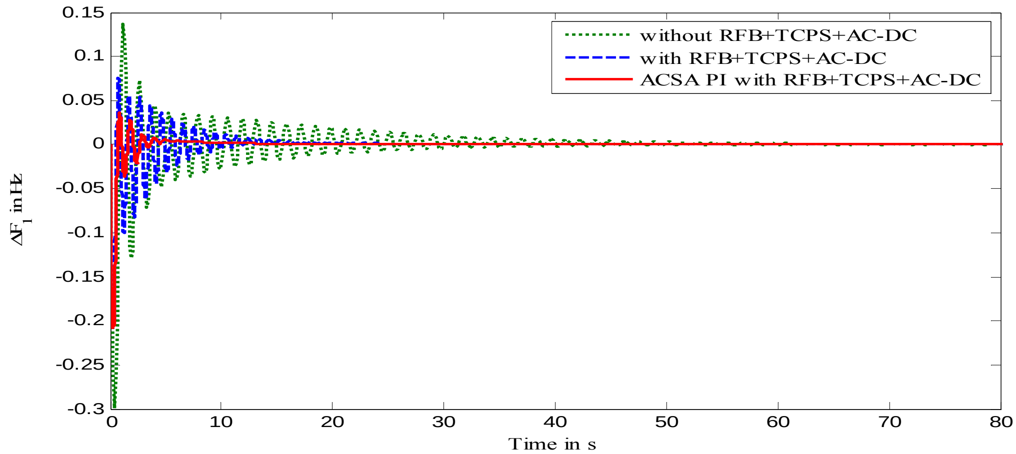

Figure-9. Frequency deviation in area-I.

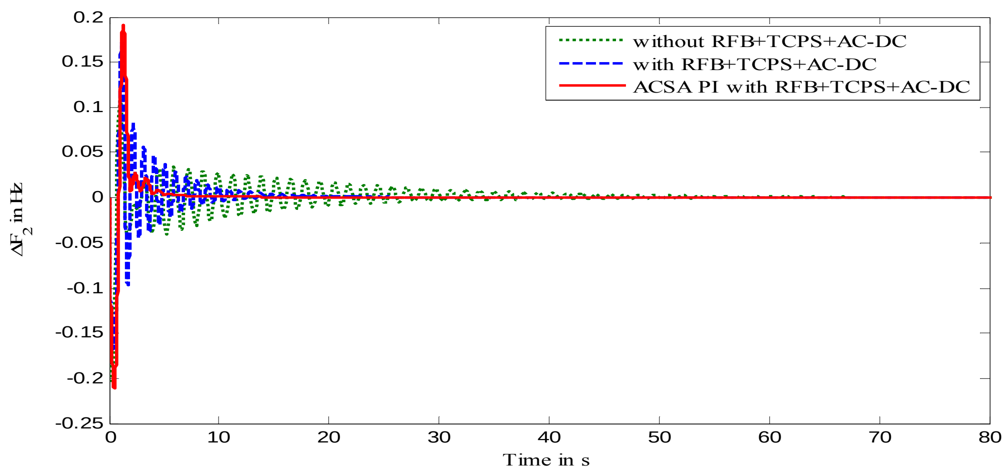

Figure-10. Frequency deviation in area-II.

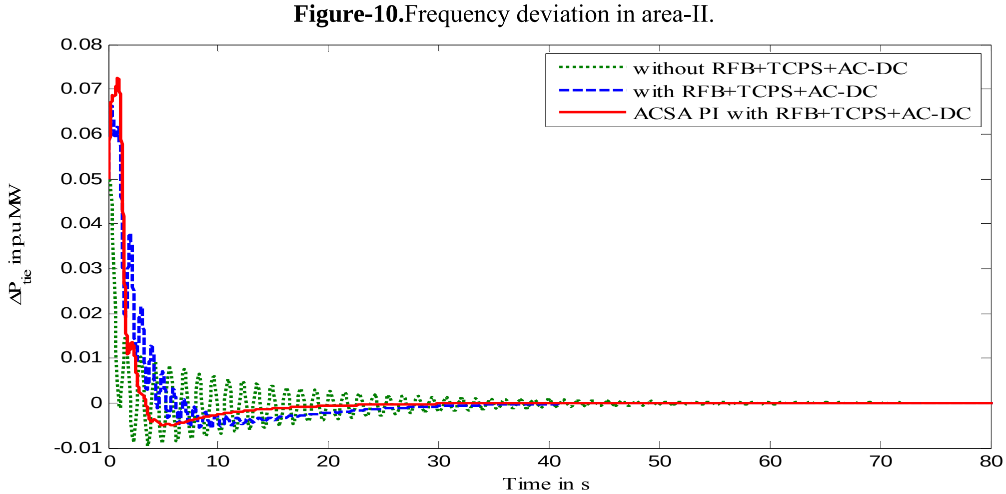

Figure-11. Inter-area tie-line power flow.

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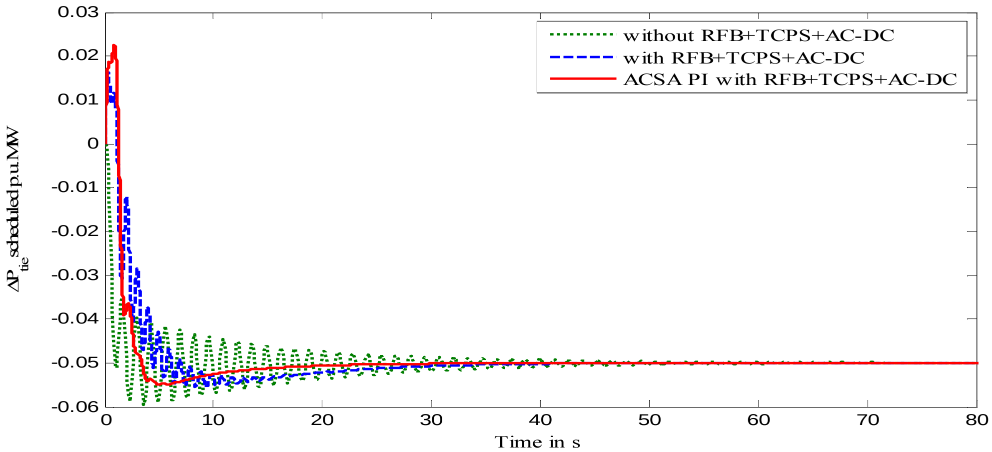

Figure-12. Scheduled tie-line power flow from area-I to area-II.

Contract violation

In this case, the DISCO-1 violates the contract by demanding 0.1 pu MW excess 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 that is GENCO-1 and GENCO-2. 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. The distribution of uncontracted load among the GENCOs is decided by the area participation factor. The simulation results for this scenario in terms of frequency deviation, tie-line power flows and scheduled tie-line power flow are given in Figure-13, Figure-14, Figure-15 and Figure-16 respectively.

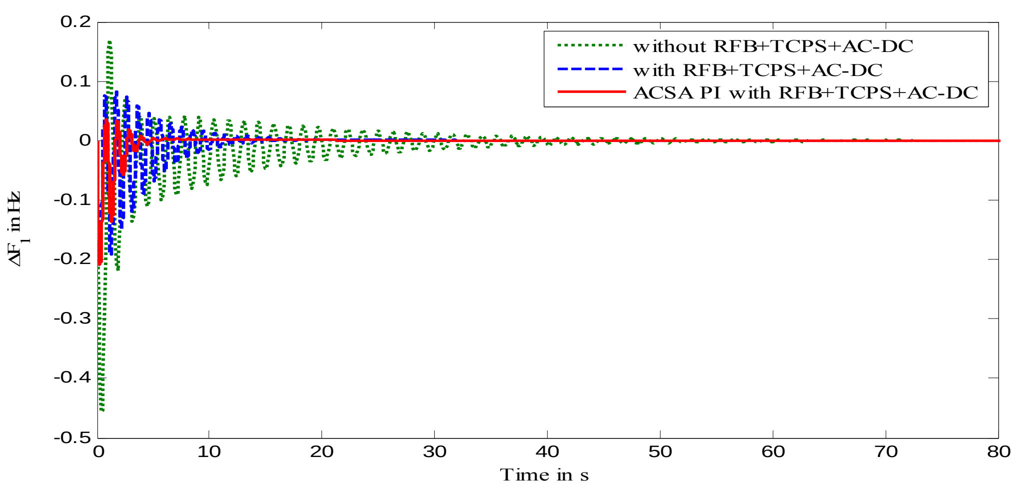

Figure-13. Frequency deviation in area-I.

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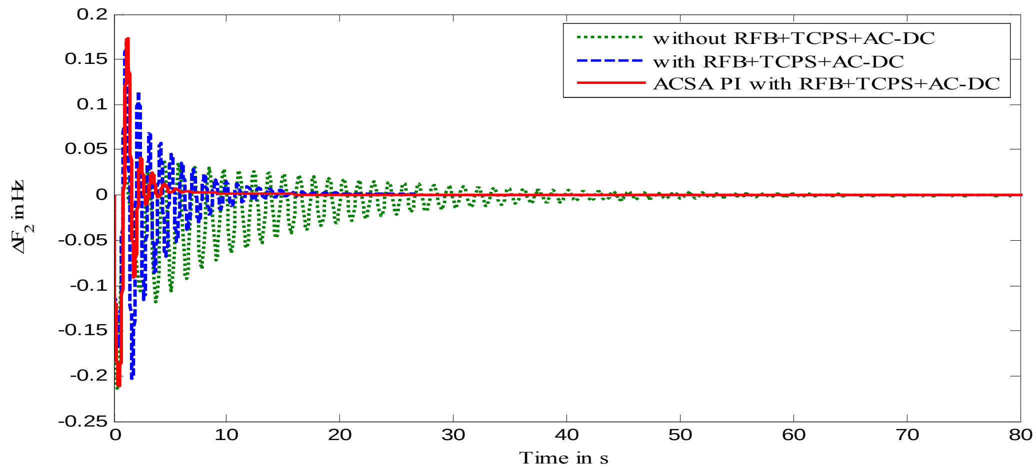

Figure-14. Frequency deviation in area-II.

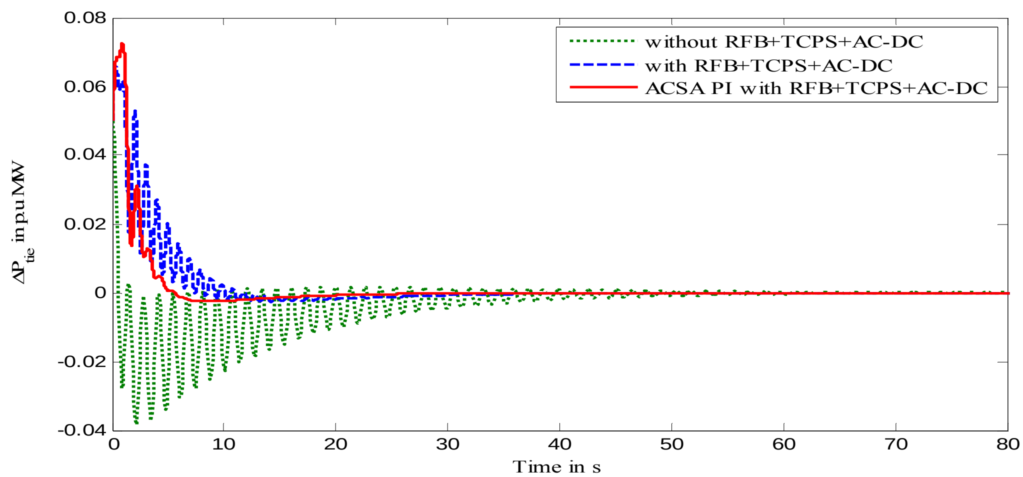

Figure-15. Inter-area tie-line power flow.

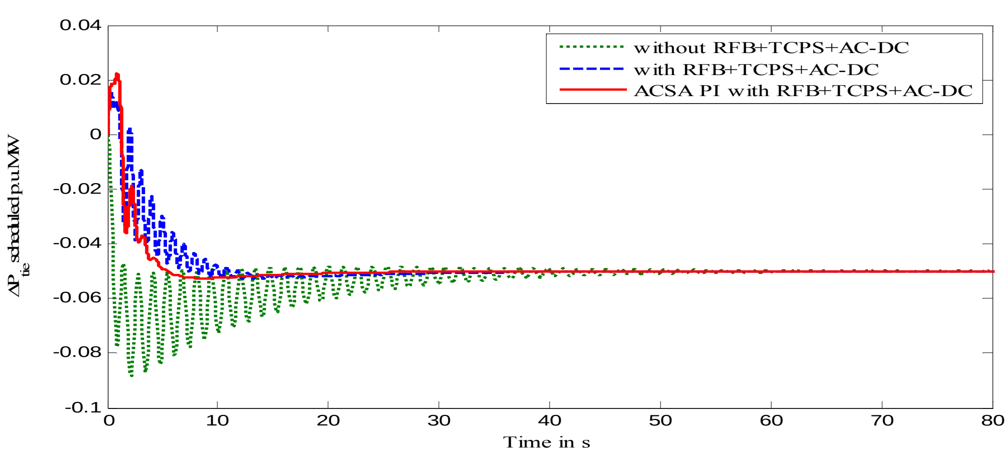

Figure-16. Scheduled tie-line power flow from area-I to area-II.

From the simulation results of all the three possible deregulation scenarios, it has been observed that the coordinated control of TCPS, RFB and AC-DC parallel tie-lines effectively damps the area frequency deviation, inter-area tie-line power deviations and decreases the settling time to a larger extend. The scheduled tie-line power flows are at their desired levels. The coordinated control has been further improved by the application of ACS algorithm tuned PI controller.

CONCLUSIONS

In this work, a new a new global search optimization algorithm, the Artificial Cooperative Search Algorithm (ACS) has been introduced for the solution of LFC problem in deregulated power environment. The proposed algorithm has been applied to tune the controller gains for a two area deregulated power system with coordinated control of TCPS, RFB and AC-DC parallel tie-lines and has been tested under various possible bilateral contracts. The simulation results reveal that the coordinated operation of TCPS, RFB and AC-DC tie-line along with controller designed using ACS algorithm suppresses the frequency deviations and tie-line power deviations effectively. The area frequency responses and tie-line power flow response exhibit less overshoot less undershoot and minimum settling time in the presence of TCPS, RFB and AC-DC parallel tie-lines.

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