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A Robust Discrete FuzzyP+FuzzyI+FuzzyD Load Frequency Controller for Multi-Source Power System in Restructuring Environment

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Abstract-*In this paper a fuzzy logic (FL) based load frequency controller (LFC) called discrete FuzzyP+FuzzyI +FuzzyD (FP+FI+FD) is proposed to ensure the stability of a multi-source power system in restructured environment. The whale optimization algorithm (WOA) is used for optimum designing the proposed control strategy to reduce fuzzy system effort and achieve the best performance of LFC task. Further, to improve the system performance, an interline power flow controller (IPFC) and superconducting magnetic energy system (SMES) is included in the system. Governor dead band, generation rate constraint, and time delay are considered as important physical constraints to get an accurate understanding of LFC task. The performance of the optimized FP+FI+FD controller is evaluated on a two area six-unit hydro-thermal power system under different operating conditions which take place in a deregulated power market and varying system parameters in comparison with the classical fuzzy PID controller. Simulation results shows that WOA based tuned FP+FI+FD based LFC controller are relatively robust and achieve good performance for a wide change in system parameters considering system physical constraints.*

Keyword: Load frequency control, FP+FI+FD, Whale optimization algorithm, Multi-source power system

NOMENCLATURE

ACE	Area Control Error
AGPM	Augmented Generation Participation Matrix
CES	Capacitor Energy System
DE	Differential Evolution
DISCO	Distribution Company
ES	Energy Storage
FACTS	Flexible Alternating Current Transmission System
FD	Fuzzy Derivative
FI	Fuzzy Integral
FL	Fuzzy Logic
FP	Fuzzy Proportional
GA	Genetic Algorithm
GDB	Governor Dead Band
GENCO	Generation Company
GRC	Generation Rate Constraint
IAE	Integral of Absolut Error
IC	Input Combination
IPFC	Inter Line Power Flow Controller
ISE	Integral of Square Error
ISO	Independent System Operator
ITAE	Integral of Time multiplied Absolut Error
ITSE	Integral of Time multiplied Square Error
LFC	Load Frequency Control
MIMO	Multi Input Multi Output
MSF-PID	Multi Stage Fuzzy PID
PFC	Polar Fuzzy Controller
PID	Proportional Integral Derivative
PSO	Particle Swarm Optimization
RFB	Redox Flow Batteries
SMES	Superconducting Magnetic Energy System
TD	Time Delay
TRANSCO	Transmission Company
UPFC	Unified Power Flow Controller
WOA	Whale Optimization Algorithm

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1. INTRODUCTION

The main objectives of LFC control are maintaining the frequency of the power system and tie-line powers in the specified values. LFC is classified in secondary level of power system control. After restructuring in power system, new participants such GENCOs, TRANSCOs, DISCOs, and ISO take part in electrical market. Thus, the main objectives of the LFC control remains and should to be more considered [1].

In a deregulated environment, classical controllers are certainly not suitable for the LFC problem. Because the real power system subjected to different kind of uncertainties and disturbances due to complexity of power system structure, approximations which, is taken to model system dynamic behavior into account, including different contracts between DISCO and GENCOs in addition with rapid change in demand of each control area. Thus, developing a new flexible and robust controller is needed to overcome these drawbacks [2-4]. In some reported researches the gains of a controller are optimized using an optimization algorithm like firefly algorithm [5, 6], DE [7], hybrid of DE and pattern search [8], bacterial foraging optimization [9] approaches. A self-adaptive modified bat algorithm based fuzzy PID controller for LFC of a multi-area power system has been reported in Ref. [10]. Also, Sahu et. al. [11] applied teaching-learning based optimization algorithm for tuning a fuzzy-PID controller for solution of the LFC problem. Focus of the above represented methods is only on optimal setting gains of the classical, intelligence or hybrid controller. The classical PID type controllers are known to give poor performance in the system transient response. Also, only optimizing the gain of fuzzy logic based PID controllers, without tuning the membership function and rules not sufficient enough to damp the frequency oscillations. In some other researches an intelligence controller were suggested or optimized for LFC task in power system. Shayeghi et. al [12] represented a novel fuzzy logic based controller called MSF-PID for LFC task in the deregulated power system. Also, in Refs. [3, 4] they used GA and PSO techniques for optimal setting the membership function of MSF-PID. Baghya and Kamaraj [13] reported a neuro fuzzy system based controller for LFC of a multi area restructured power system. Although, they considered GRC for thermal units but important physical limits like GDB and TD are ignored. A new PFC was proposed for solving LFC problem in Ref. [14]. Yousef [15] presented an adaptive fuzzy logic based controller for LFC task. Power system nonlinearities ignored in the above studies and then exact proficiency of these controllers were not evaluated in real world LFC system. Results of the above literature indicated that the fuzzy type controllers have strong capabilities for solution of the power systems load frequency control. Authors in Ref. [16] were proposed a multi-objective harmony search algorithm for optimal tuning of the multi-stage fuzzy PID controller in a multi area power system without system nonlinearities. In addition, the novel advanced power electronic based devices such as ES systems, FACTS devices in coordinated (or uncoordinated) with LFC controllers are proposed in recently literature to improve the performance of the general LFC strategies. Shayeghi et. al [2] by including a SMES to system, enhanced the performance of the H2/H∞ based LFC controller. Authors in Ref. [8] had done a LFC task for a multi-area power system with the presence of RFB and UPFC devices. Impact of integrator controller including Thyristor controlled series compensator for solving LFC problem has been investigated in a restructured power system [17]. Raja and Asir in [18] considered the effect of CES on artificial neural network based AGC. In these studies, system nonlinearities such as GRC, GDB and TD were ignored. In Ref. [19] a PID controller with a filter in its output and optimized by DE algorithm, was used for LFC task in a multi-area multi-source power system. Furthermore, to improve the system performance authors added an IPFC in the tie-line and a RFB in the control area. Also, GRC and TD were considered as the physical constraints.

In this paper, a parallel discreet FP+FI+FD controller is proposed for LFC task in a multi-source restructured power system. This controller has nine control parameters and this characteristic gives it high order of freedom and a very robust behavior for controlling any complex system with high nonlinearities [20, 21]. Structure of this controller is based on three parts, fuzzy proportional, fuzzy integrator, and fuzzy derivative. Each of this parts consist of a fuzzy logic rule base controller and classical controllers i.e. a combination of time domain integrators and derivatives. Incorporation of the rule based fuzzy logic with the conventional PID controllers is caused that the proposed FP+FI+FD controller has the properties of both classical and fuzzy controllers and makes it a high robust and strong controller [20-23]. Due to discreet nature of the proposed FP+FI+FD controller in the first stage, a tow area six-unit power system are selected and discretized using a specified sampling time. In order for a fuzzy type controller to perform well, the fuzzy sets should be carefully designed. A major problem plaguing the effective use of the FP+FI+FD controller is the difficulty of correctly tuning control parameters and constructing the membership functions. Because, it is a computationally expensive combinatorial optimization problem. In view of this, in the next stage, the proposed control strategy structure should be optimized to achieve better control system and reduce fuzzy system effort. For this mean, the system control design procedure is modeled as an optimization problem and solved using the whale optimization algorithm [24]. It can be considered a global optimizer because it includes exploration/exploitation ability. Furthermore, the proposed hypercube mechanism defines a search space in the neighborhood of the best solution and allows other search agents to exploit the current best record inside that domain. The other main advantage of the WHO is that, has two control parameter should be fine-tuned. Stability analysis and also suitable time domain simulations are used to evaluate the performance of the proposed controller. The effectiveness of the proposed WOA based FP+FI+FD optimized controller is evaluated under different operating conditions which take place in a deregulated power market and varying system parameters.

2. MATERIALS AND METHODS

2.1. Market based model of LFC system

In a traditional power system, generation, transmission, and distribution integrated with possession of a single owner, usually the government. However, in the deregulated environment this is no longer exist, but the main goal of LFC like maintaining frequency deviation and tie-line power scheduling in zero for the steady state case is remain [2]. GENCOs, TRANSCOs, DISCOs, and ISO are main components of restructured power system. The block diagram of each control area for restructured power system is shown in Fig. 1 (For more details see Ref. [4]).

The solid lines in Fig. 1 are same as the conventional power system, and the dashed lines are indicating the presence of deregulation effects on the LFC system model. ΔP_{di} denotes the total load demand of ith area, apf_{ki} is the area control error (ACE) participation factor of GENCO$_{k\text{-}i}$ and

$$\sum_{k=1}^{n_i} apf_{ki} = 1 \tag{1}$$

$\Delta P_{Loc,i}$ denotes the total contracted load demands which is given by:

$$\Delta P_{Loc,i} = \sum_{j=1}^{m_j} \Delta P_{Lj-i} \tag{2}$$

Where, $\Delta P_{Lj\text{-}i}$ is the load demand of DISCO$_{j\text{-}i}$. ξ_i is the total contract tie-line power flows from other areas to area#i which can be expressed as

$$\xi_i = \sum_{k=1,k\neq i}^{N} \Big(\sum_{j=1}^{n_i}\sum_{t=1}^{t_i} gpf_{(s_i+k)(z_j+t)} \Delta P_{Lt-k} - \sum_{t=1}^{n_k}\sum_{j=1}^{m_i} gpf_{(s_k+t)(z_i+j)} \Delta P_{Lj-i}\Big) \tag{3}$$

and ρ_{ki} as given by Eq. (4) is the contract load demand of GENCO$_{k\text{-}i}$ due to load demands from other areas [25],

$$\rho_{ki} = \sum_{j=1}^{N}\left(\sum_{t=1}^{m_j} gpf_{(s_i+k)(z_j+t)} \Delta P_{Lt-j}\right) \tag{4}$$

In restructured power system, GENCOs may or may not engage in the LFC task and DISCOs can contract with any available GENCOs in their own or another area. Therefore, different combinations are available between DISCOs and GENCOs to contract together. ISO or other responsible organization have to clear all the transactions. AGPM is an idea which used to express the possible contracts [2]. This matrix shows the participation factor of a GENCO in the load following contract with a DISCO. The rows and columns of AGPM equal to the total number of GENCOs and DISCOs in entire power system, respectively. Consider the number of GENCOs and DISCOs in the ith area to be n_i and m_i, respectively. Also, power system has N control areas. Then Eq. (5) shows the AGPM structure.

$$AGPM = \begin{bmatrix} AGPM_{11} & \cdots & AGPM_{1N} \\ \vdots & \ddots & \vdots \\ AGPM_{N1} & \cdots & AGPM_{NN} \end{bmatrix} \tag{5}$$

Where,

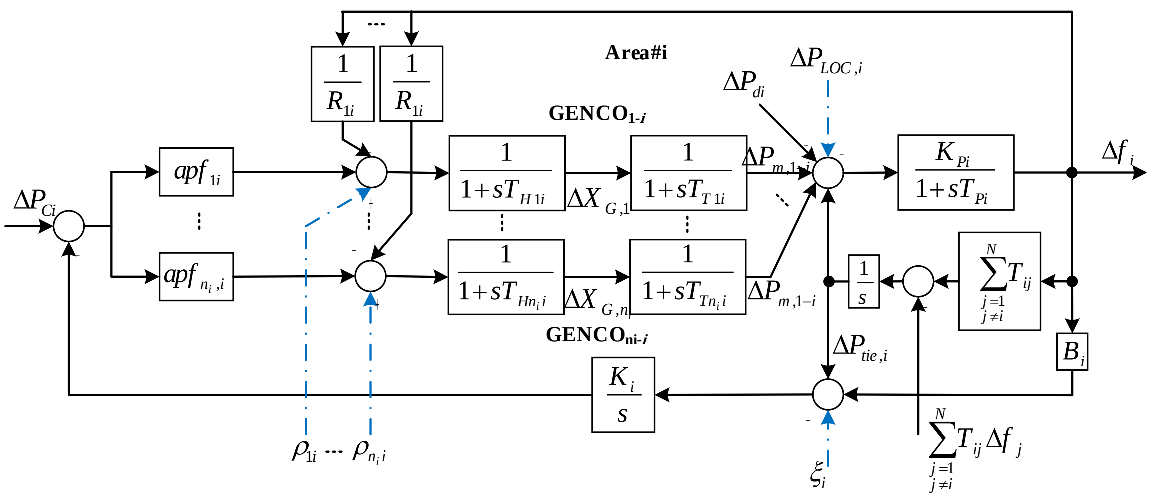


Fig. 1. Block diagram of control area#i

$$AGPM_{ij} = \begin{bmatrix} gpf_{(s_i+1)(z_j+1)} & \cdots & gpf_{(s_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ gpf_{(s_i+n_i)(z_j+1)} & \cdots & gpf_{(s_i+n_i)(z_j+m_j)} \end{bmatrix}$$

For $i,j = 1,\ldots, N$,

$$s_i = \sum_{k=1}^{i-1} n_i, z_j = \sum_{k=1}^{j-1} m_j \text{ and } s_1 = z_1 = 0$$

Sum of entries in each column of AGPM is unity. Also, $gpf_{i,j}$ refers to generation participation factor and shows the participation factor of GENCO i in total load following need of DISCO j base on contracted scenario.

Hence, using the ACE as feedback signal for control system ensures the two objectives, and increases the stability of system. ACE signal for area i defined as Eq. (6) [26]:

$$ACE_i = \Delta P_{tie,i-error} + B_i \Delta f_i \tag{6}$$

Where, $\Delta P_{tie.i\text{-}error}$ is the error between $\Delta P_{tie.i}$, the scheduled tie-line power flow deviation from other areas to area i, and can be obtained [26]:

$$\Delta P_{tie,i-error} = \Delta P_{tie,i} - \xi_i \tag{7}$$

In traditional power system there is no tie-line power flow ξ_i. Thus, in the deregulated power system contracts effects on both local area load demand and tie-line power flows. The differences between traditional and restructured environments is that, in the conventional case, the load disturbances affect the other areas only through tie-line but in deregulated situation through both tie-line and various contracts. In conventional power system, tie-line power flows after disturbance rejection stabilized at zero, but in the restructured power system tie-line power flows have to return at a value based on different contracts between GENCOs and DISCOs. Various contracts between GENCOs and DISCOs in entire power system make the disturbance rejection a difficult problem. Hence, in this paper a fuzzy logic type control strategy optimized by WOA algorithm, called parallel FP+FI+FD controller coordinated with IPFC and SMES units to overcome this problem.

2.2. Proposed FP+FI+FD controller

Fuzzy system control is one of the most successful issues in the application of fuzzy theory [27]. On the other hand, as aforementioned conventional control methods may not give satisfactory solutions to LFC task in deregulated environment. Thus, their robustness and reliability make fuzzy controllers useful to overcome these problems [28]. The block diagram of the proposed parallel FP+FI+FD controller is shown in Fig. 2 in discrete time domain. Where T>0 is the sampling time, $y_{SP}(nT)$ is the reference set-point, $y(nT)$ is the process variable, $e(nT)= y_{SP}(nT)-y(nT)$ is the error signal, and $U_{P+I+D}(nT)$ is the output of the parallel FP+FI+FD controller. This control strategy combines of fuzzy proportional (FP), fuzzy derivative (FD) and fuzzy integral (FI) controllers. The parallel FP+FI+FD control action can be obtained by algebraically sum of fuzzy P control, fuzzy I control and fuzzy D control actions, simultaneously [20].

According to Fig. 2, the proposed controller has three main parts, fuzzy P, fuzzy I, and fuzzy D controllers. Each of this controllers independently have its own responsibility i.e. the FP part has a tendency to make a system faster. The fuzzy derivative part's main duty is reducing the fast change and large overshoots in control inputs, that may be occur due to practical constraints. For reduction of the steady state error and rejecting disturbances in control system, fuzzy integral stage has been proposed.

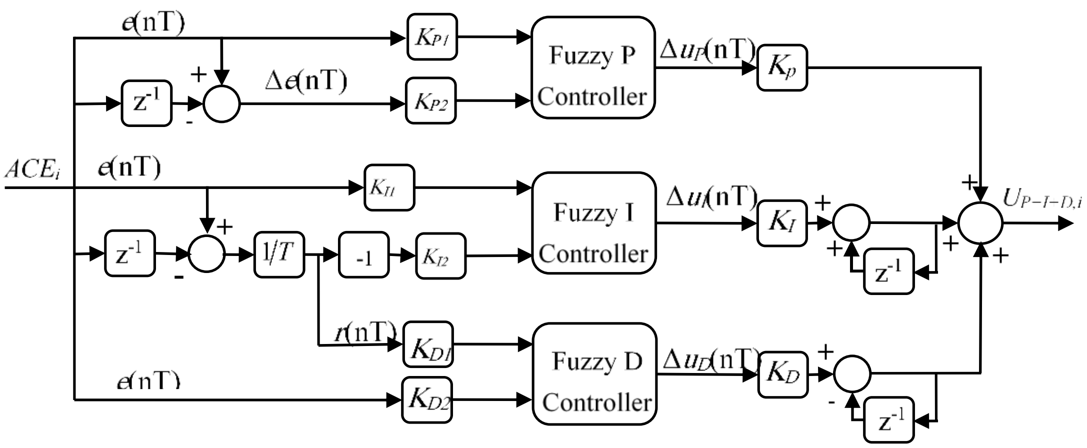


Fig. 2. Block diagram of the proposed FP+FI+FD controller

The final result, which is the sum of this three part outputs, is a control signal that makes system stable and faster.

$$u_{P+I+D}(nT) = K_P u_P(nT) + u_I(nT - T) + K_I \Delta u_I(nT) - u_D(nT - T) + K_D \Delta u_D(nT) \quad (8)$$

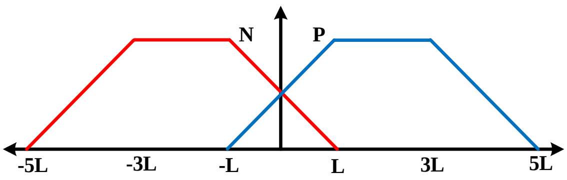
Where, u_P(nT) and K_P are the FP controller action and gain, Δu_I(nT) and K_I are the incremental control action and gain of FI controller, Δu_D(nT) and K_D are the incremental control action and gain of FD controller. Fuzzy P controller makes decision based on two input signals, error signal and its difference value which modulated using K_{P1} and K_{P2} gains, respectively. Both fuzzy I and fuzzy D controllers have the same situation with the exception that, they are using minus of derivative and derivative instead of difference of error signal, respectively. Also, K_{I1}, K_{I2}, K_{D1}, and K_{D2} are modulation gains of this controller, as depicted in the Fig. 2. Due to increasing the control parameters in the FP+FI+FD controller, the degree of freedom is increased than the conventional PID controller and then the user has more flexibility to achieve the desired level of system response.

Also, the other part of control strategy is finding the limits of membership functions in input and output control signals of fuzzy controllers, i.e. L. For the fuzzy P, fuzzy I, and fuzzy D two triangular membership functions in input variables as shown in Fig. 3(a) and three singleton membership functions in the output variable controllers as shown in Fig. 3(b)is used. In Fig. 3, L is adjustable parameter and has an important role in performance of the proposed FP+FI+FD controller [20, 21].

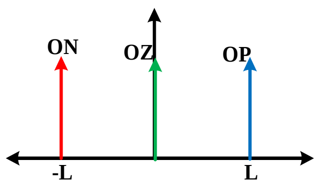
Note that, to achieve the best performance of the proposed FL type PID controller, its gains and membership functions have to be optimally tuned carefully. A major problem plaguing the effective use of the FP+FI+FD controller is the difficulty of correctly tuning control parameters (*i.e.*: K_p, K_{p1}, K_{p2}, K_I, K_{I1}, K_{I2}, K_D, K_{D1}, and K_{D2}) and constructing the membership functions. Because, it is a computationally expensive combinatorial optimization problem and also tuning of them from the trial-error method may be tedious and time consuming. Thus, one part of the optimization procedure is optimizing these nine parameters for FP+FI+FD controller. The other part of optimization is finding the limits of membership functions in input and output control signals of fuzzy controllers as shown in Fig. 3(a)-(b). Hence, in this study, optimization of variable L at (500-1000) coordinated with other nine control parameter of the proposed FL type PID controller are proposed. For this reason, the whale optimization algorithm is used for optimally setting the proposed control strategy to reduce fuzzy system effort and take large LFC system uncertainties and nonlinearities into account. WOA can be considered a global optimizer because it includes exploration/exploitation ability. Furthermore, the proposed hypercube mechanism defines a search space in the neighborhood of the best solution and allows other search agents to exploit the current best record inside that domain [24]. Also, rule-based with the four control rules, max-min inference mechanism and center of mass for defuzzification of the proposed control strategy are considered. The fuzzy rules are given in Table 1 [20, 23].

2.3. Whale optimization algorithm

The whale optimization algorithm is inspired from bubble-net foraging behavior of humpback whales.



(a)



(b)

Fig. 3. Membership functions of fuzzy controllers

Table 1. Fuzzy rules of FP+FI+FD controller

First input	Second input	Output		
		Fuzzy P	Fuzzy I	Fuzzy D
N	N	OZ	ON	OZ
N	P	OP	OZ	ON
P	N	ON	OZ	OP
P	P	OZ	OP	OZ

The mathematical model of the WOA consists of three parts. Encircling the prey, bubble-net attacking method (exploitation phase), and searching for prey (exploration phase). The WOA assumes that the current best solution is the location of prey (optimum solution or near optimum solution). After finding the best solution the other search agents try to update their position according to position of the best solution using Eqs. (9) and (10).

$$\vec{D} = |\vec{C}.\vec{X}^*(t) - \vec{X}(t)| \quad (9)$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A}.\vec{D} \quad (10)$$

where, t is the current iteration, A and C are coefficient vectors,

X^* is the position vector of the best solution so far, X is the position vector, | | is the absolute value and (.) is an element by element multiplication. A and C are calculated using Eqs. (11) and (12).

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \tag{11}$$

$$\vec{C} = 2\vec{r} \tag{12}$$

where, a is decreased from 2 to 0 linearly and r is a random vector in [0,1]. For bubble-net attacking behavior two strategies are considered where it is assumed the humpback whale selects one of them by a probability of 50 percent. First strategy is shrinking encircling mechanism and the second one is spiral updating position [24]. Then the mathematical formulation of search agent position updating during the optimization procedure is given by Eq. (13).

$$\vec{X}(t+1) = \begin{cases} \vec{X}^*(t) - \vec{A}.\vec{D} & if \quad \rho < 0.5 \\ \vec{D}' e^{bl}.\cos(2\pi l) + \vec{X}^*(t) & if \quad \rho \geq 0.5 \end{cases} \tag{13}$$

where, $\vec{D}' = |\vec{X}^*(t) - \vec{X}(t)|$ and indicates the distance of the i^{th} whale to the best solution obtained so far, b is a constant for defining the shape of the logarithmic spiral, l is a random number in [-1,1]. Exploration phase (search for prey) can be modeled in same way using Eqs. (14) and (15).

$$\vec{D} = |\vec{C}.\vec{X}_{rand} - \vec{X}| \tag{14}$$

$$\vec{X}(t+1) = \vec{X}_{rand} - \vec{A}.\vec{D} \tag{15}$$

where, $|A|>1$ emphasize the exploration and allows the WOA to searching for global optima solution. X_{rand} is a random position vector (of a random whale) chosen from the current populations. Fig. 4 shows the flowchart of the WOA algorithm. WOA can be considered a global optimizer because it includes exploration/exploitation ability. Furthermore, the proposed hypercube mechanism defines a search space in the neighbor hood of the best solution and allows other search agents to exploit the current best record inside that domain. Adaptive variation of the search vector A allows the WOA algorithm to transit smoothly between exploration and exploitation: by decreasing A, some iterations are devoted to exploration ($|A|\geq 1$) and the rest is dedicated to exploitation ($|A|<1$). Notably, WOA includes only two main internal parameters to be adjusted (A and C).

2.4. LFC Model of SMES and IPFC

Matching of demand and power supply is always a complex process, especially at peak loads for reliable operation of the power system. Thus, it is necessary to include energy storage systems practically in the present deregulated scenario to enhance LFC task. On the other hand, optimized LFC controllers can reject small load disturbances during a time interval depend on the severity of disturbance. As the governor is a mechanical system with low speed, it can't overcome some severe disturbances which occur in power system. So, energy storage systems like SMES, RFB, CES and etc. with high speed can be used to absorb the frequency deviation of the power system. SMES has a good performance in normal temperature, small loss and long service life [2]. Here, the SMES system is included in the multi-source deregulated power system to achieve the best LFC performance. The transfer function model of SMES is given in Fig. 5.

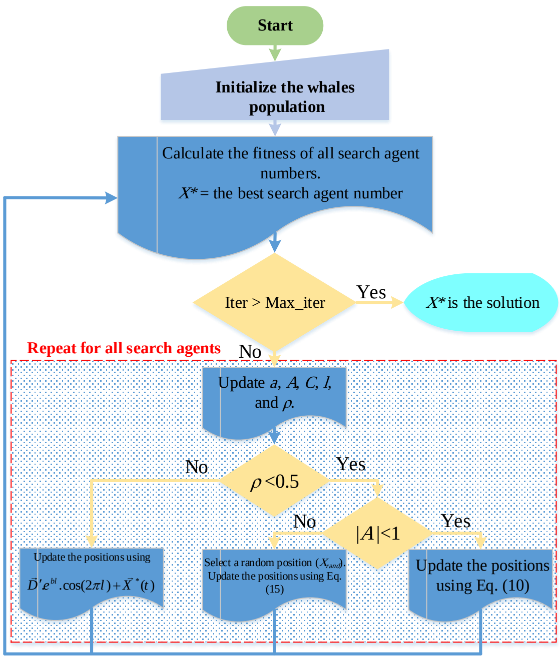


Fig. 4. The flowchart of the WOA algorithm

Area control error is considered as SMES input signal in this paper [2].

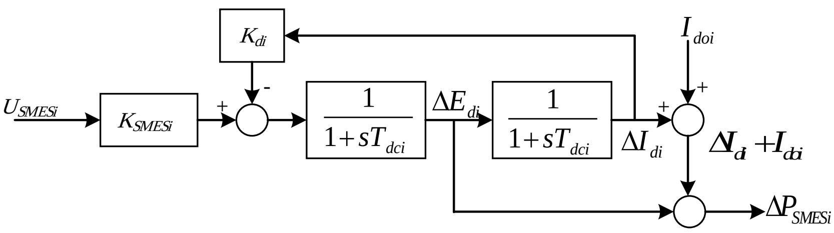


Fig. 5. The transfer function model of SMES

Note that, FACTS devices play a vital role to control the power flow in an interconnected power system. Many studies have reported the potential of using FACTS devices such as UPFC and IPFC controllers for better control of power system [19].

The IPFC is attractive for control of multi-area power systems since it not only can make power flow control for multi-line transmission system but can compensate each transmission line separately or concurrently. In view of economical point, an IPFC is included in this work. It is placed in the tie-line which can increase its power transfer capability. The transfer function model of an IPFC can be expressed by Eq. (see Ref. [19] for more details).

$$\Delta P_{ipfc} = \frac{1}{1+sT_{ipfc}}(K_1\Delta F_i - K_2\Delta P_{tie}) \tag{16}$$

Where, K_1 and K_2 are feedback gains and T_{ipfc} is its time constant in seconds.

2.5. Power system under study

A two area multi-source interconnected power system has been considered for LFC in deregulated environment. Block diagram representation of two area six unit power system including SMES and IPFC devices and system physical constraints such as GRC, GDB and TD in deregulated environment is shown in Fig. 6. Each area comprises of three GENCOs with two thermal reheat systems, a hydropower system, and two DISCOs. GRC is considered as 3%/min for thermal unit, 270%/min for rising generation and 360%/min for lowering generation of hydropower system. In the present work, a time delay of 50 ms is considered. GDB is another non-linearity constraint that considered as 0.036% in this paper [6]. The other relevant parameters are given in Appendix.

2.6. Objective function and problem formulation

Note that the properly choice of fitness function is very important in synthesis procedure of the proposed discrete fuzzy controller. Because different cost functions promote different WOA behaviors, which generate fitness value providing a performance measure of the problem considered. Moreover, the objective function should be considered the desired specifications and constraints. Performance criteria usually used in the control design are ITAE, ISE, ITSE, and IAE indices. ITAE based tuned controllers, reduces the settling time better than IAE and ISE based tunings one. Controller tuning based on ITSE criteria, lead to large output of controller for sudden disturbances and this is a disadvantage for this criteria. As reported in the literature the ITAE criteria is the best performance index for tuning controller parameters using heuristic algorithms [19]. Thus, the discrete form of ITAE index is used as a cost function for optimized the proposed controller structure as follows:

$$\begin{aligned} J = \sum_{n=1}^{NS} T\,(|\,\Delta F_1(nT\,)\,| + |\,\Delta F_2(nT\,)\,| \\ + 10\times|\,\Delta P_{tie,error}\,(nT\,)) \end{aligned} \tag{17}$$

where, T is sampling time (equal to 0.05 sec), NS is number of samples, ΔF_1 and ΔF_2 are frequency deviation of area 1 and 2, respectively. $\Delta P_{\text{tie,error}}$ is the error of tie- line power from its scheduled value. In this paper 600 samples are used for optimization procedure. Then simulation time equals to 600×0.05 = 30 seconds.

First we have to discretize transfer function of power system under study, due to the discrete nature of the FP+FI+FD controller. Discretizing is performed by "*slmdldiscui*" command in MATLAB software [23]. In this way sampling time has been considered to be T = 0.05. Note that in simulations n is an integer i.e. $n \in \mathbf{N}$.

Table 2. Parameters of the proposed FP+FI+FD controller for system with SMES & IPFC

Variable	K_p	K_{p1}	K_{p2}	K_i	K_{i1}	K_{i2}	K_d	K_{d1}	K_{d2}	L
Value	1.2935	-1.6637	0.8587	-0.4416	0.1822	-0.3686	-0.0046	0.0495	0.0157	720

Table 3. Parameters of the proposed FP+FI+FD controller and fuzzy PID controller for system without SMES & IPFC

FP+FI+FD controller

Variable	K_p	K_{p1}	K_{p2}	K_i	K_{i1}	K_{i2}	K_d	K_{d1}	K_{d2}	L
Value	-1.3122	-0.4205	-0.4501	0.1497	-0.3714	-0.4021	0.0396	-0.0345	-0.0247	692

Fuzzy PID controller

Variable	K_1	K_2	K_3	K_4	K_5
Value	-4.9254	-1.1346	-0.0488	-0.2745	-0.4801

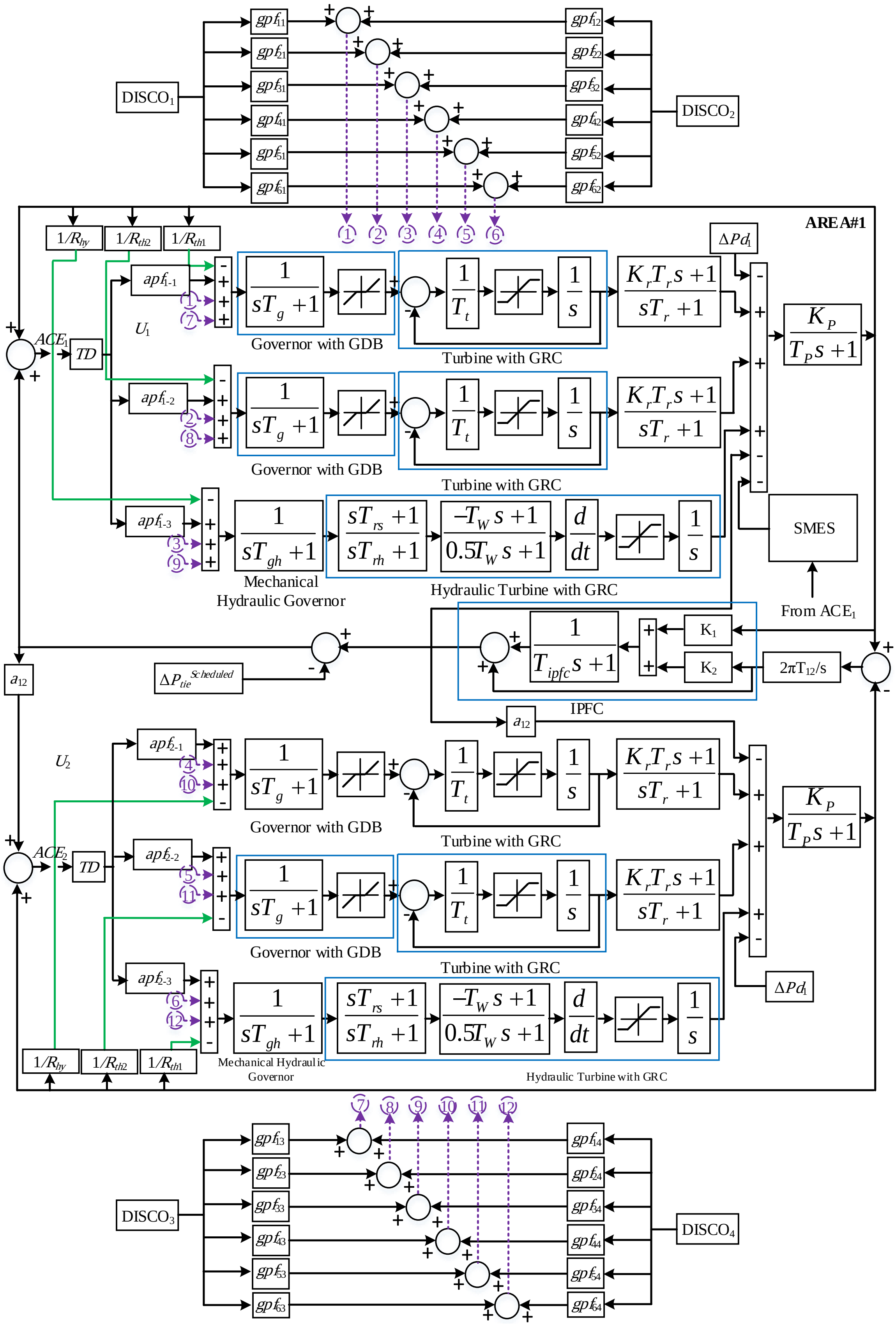


Fig. 6. Block diagram representation of two area six unit power system with SMES and IPFC in deregulated environment

Table 4. α1 for all 12 IC regions of FP+FI+FD controller

IC regions	Value of α1
IC 1 & IC 3	$\left\lvert \frac{LK_P(K_{P2}-K_{P1})}{2(2L-K_{P1}M_e)}+\frac{LK_I(\mathrm{T}K_{I2}+K_{I1})}{2T(2L-K_{I1}M_e)}+\frac{LK_D(\mathrm{T}K_{D2}-K_{D1})}{2T(2L-K_{D2}M_e)} \right\rvert$
IC 2 & IC 4	$\left\lvert \frac{LK_P(K_{P2}-K_{P1})}{2(2L-K_{P2}M_{\Delta e})}+\frac{LK_I(\mathrm{T}K_{I2}+K_{I1})}{2T(2L-K_{I2}M_r)}+\frac{LK_D(\mathrm{T}K_{D2}-K_{D1})}{2T(2L-K_{D1}M_r)} \right\rvert$
IC 5	$\left\lvert \frac{K_PK_{P2}}{2}+\frac{K_IK_{I2}}{2T}-\frac{K_DK_{D1}}{2T} \right\rvert$
IC 6	0
IC 7	$\left\lvert \frac{K_IK_{I1}}{2}+\frac{K_DK_{D2}}{2}-\frac{K_PK_{P1}}{2} \right\rvert$
IC 8	0
IC 9	$\left\lvert \frac{K_PK_{P2}}{2}+\frac{K_IK_{I2}}{2T}-\frac{K_DK_{D1}}{2T} \right\rvert$
IC 10	0
IC 11	$\left\lvert \frac{K_IK_{I1}}{2}+\frac{K_DK_{D2}}{2}-\frac{K_PK_{P1}}{2} \right\rvert$
IC 12	0

For objective function calculation, the discrete domain simulation of the multi-area LFC system model as given in Fig. 6 is carried out for the simulation period. It is aimed to minimize this objective function in order to find better FP+FI+FD system effort for LFC task. Thus, the design procedure is formulated as the Eq. (18) constraint optimization problem, where their constraints are FP+FI+FD parameters limits. The upper and lower limits are considered as ±10, ±5, and ±2 for fuzzy P, fuzzy I, and fuzzy D controllers gains, respectively. L is considered at range of 500 to 1000 [20, 21].

$$\begin{aligned}&\text{minimize } J\\&\text{subject to:}\\&K_P^{\min}<K_P,K_{P1},K_{P2}<K_P^{\max}\\&K_I^{\min}<K_I,K_{I1},K_{I2}<K_I^{\max}\\&K_D^{\min}<K_D,K_{D1},K_{D2}<K_D^{\max}\\&L_{\min}<L<L_{\max}\end{aligned} \tag{18}$$

2.7. Optimization results

In this study, to achieve the desired level of the overall system dynamical performance in a robust way, the above optimization problem is solved using the WOA technique to search for optimal or near optimal set of FP+FI+FD controller parameters. Optimal parameters of the FP+FI+FD controller and a fuzzy PID type controller introduced in Ref. [23] for comparison obtained by WOA algorithm are tabulated in Tables 2 and 3 including IPFC and SMES devices and without them, respectively. In this way, the number of whale populations (search agent number) is considered equal to 30. Also, maximum number of iterations (*MI*) is taken as 50. Fig. 7 shows the fitness function minimization procedure.

3. RESULTS AND DISCUSSION

In this section, firstly in scenario 1 stability analysis of the proposed FP+FI+FD controller in the power system with SMES and IPFC is done. Then based on load disturbances, load contracts between GENCOs and DISCOs and varying LFC system parameters different operation scenarios are defined and performance of the proposed controller is evaluated in time domain based simulations including GDB, TD and GRC nonlinearities.

3.1. Scenario 1 (stability analysis)

To know the parameters variation region for which the controller operation will be successful, stability analysis of the control system is provided in this section. Using the Ref. [22] theorem 1 is described as:

Theorem 1: If the process under control denoted by R, the sufficient condition for nonlinear FP+FI+FD control system is to be stable are:

1. The process under control has a bounded norm (gain) i.e., $\|R\|_\infty<\infty$.
2. The parameters of FP+FI+FD controller satisfy Eq. (19).

$$\alpha_1\|R\|<\infty \tag{19}$$

where, α_1 is different for any input combination (IC) regions of FP+FI+FD controller [20-22], and are given in Table 4.

First stage of the stability analysis is to calculate H_∞- norm of the power system under study [22]. The H_∞- norm of a discrete time system is the peak gain of the frequency response, and it is infinite if system has poles on unit circle. In this paper, H_∞-norm of the proposed multi-area multi-unit power system calculated considering multi-input multi-output (MIMO) nature of the system. Equation (20), which is described in [29] is used for calculating H_∞-norm in a MIMO system.

$$\|R(z)\|_\infty = \max_{\theta\in[0,\pi]} \sigma_{\max}(R(e^{j\theta})) \tag{20}$$

where, $\sigma_{\max}(.)$ denotes the largest singular value of a matrix. For a MIMO system, the H_∞-norm is the peak gain across all input/output channels. The H_∞ norm is infinite if R has poles on the imaginary axis (in continuous time), or on the unit circle (in discrete time). R is the system under study. Using the Eq. (21), the maximum value of H_∞-norm for all input/output channels of the LFC system under study is obtained as:

$$\|R(z)\|_\infty = 6.1237<\infty \tag{21}$$

The second stage of the stability analysis is to calculate α_1 for all 12 IC regions as given in Table 4. Results of the stability analysis of the FP+FI+FD controller for the proposed MIMO multi-source power system is shown in Table 5.

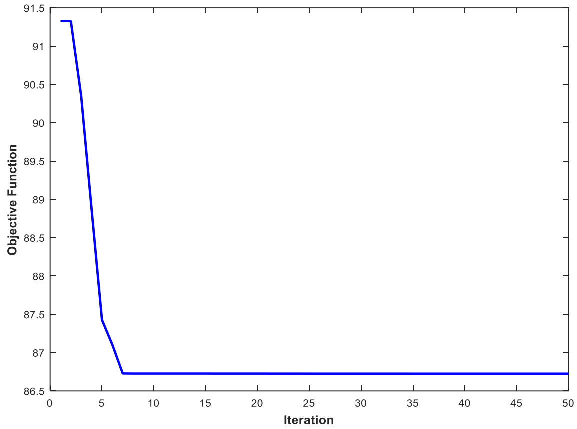


Fig. 7. Minimizing fitness function by tuning FP+FI+FD controller with IPFC & SMES

Table 5. Value of α1 and α1×R for all 12 IC regions of FP+FI+FD controller applied to MIMO system

IC regions	Value of α_1	$\alpha_1\times\|\|R\|\|_\infty$
IC 1 & IC 3	1.6104	9.8617
IC 2 & IC 4	1.6091	9.8536
IC 5	2.1855	13.3832
IC 6	0	0
IC 7	1.0357	6.3424
IC 8	0	0
IC 9	2.1855	13.3832
IC 10	0	0
IC 11	1.0357	6.3424
IC 12	0	0

From Eqs. (20) and (21) and Table 5, sufficient conditions for stability of the FP+FI+FD controller applied to the proposed LFC MIMO system for all 12 IC regions has obtained, and according to Theorem 1, the power system under study equipped with the proposed FP+FI+FD controller, SMES, and IPFC is stable.

3.2. Scenario 2

In this scenario, DISCOs have freedom to have a contract with any GENCOs in their or another area. Following AGPM is considered for this scenario:

$$\mathrm{AGPM} = \begin{bmatrix} 0.3 & 0.35 & 0 & 0.5 \\ 0.2 & 0.2 & 0.5 & 0 \\ 0.1 & 0.1 & 0 & 0 \\ 0 & 0.25 & 0.25 & 0 \\ 0.3 & 0 & 0 & 0.5 \\ 0.1 & 0.1 & 0.25 & 0 \end{bmatrix} \tag{22}$$

It is assumed that the load step of 0.2, 0.05, 0.15, and 0.1 are demanded by DISCOs 1, 2, 3, and 4, respectively. Also, load disturbances of 15% and 10% is considered for areas 1 and 2, respectively. To encounter the controllers in a challenging situation, the time constants of governor in thermal power plants (T_{sg}) is increased by 25% from nominal value. Following four control methods are compared in simulations:

i. Fuzzy PID controller without IPFC & SMES.

ii. FP+FI+FD controller without IPFC & SMES.

iii. FP+FI+FD controller with IPFC.

iv. FP+FI+FD controller with IPFC & SMES.

Based on Eq. (3) the tie-line power has to be scheduled at -0.0425 pu. Power system responses in this scenario are depicted in Fig. 8. This figure proves the superiority of the proposed control strategy in comparison with other control methods.

Table 6. Comparison of time domain performance indices for scenario 1

	Control Method	Overshoot [%]	Settling Time [n]	ITAE	ISE
ΔF_1	(i)	0.1444	35	92.2173	3.7881
	(ii)	0.1145	30	52.0935	2.4934
	(iii)	0.129	17	18.8287	0.931
	(iv)	0.0989	14	18.5713	0.8145

Based on the Fig. 8, in respect of the frequency deviation SMES is preferable than IPFC (Figs. 8(a) and 8(b)) and in respect of the tie-line power flow IPFC is much better than SMES (Fig. 8(c)). Also, time domain performance indices calculated for in this scenario and are shown in Table 6.

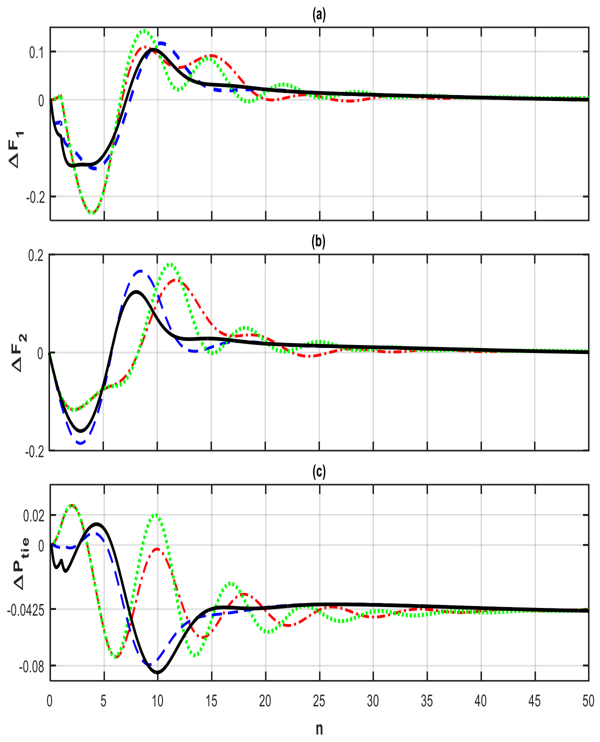


Fig. 8. Deviation of frequency and tie line power flow in scenario#2; Dotted: method (i), Dashed-Dotted: method (ii), Dashed: method (iii), Solid: method (iv)

3.3. Scenario 3

In this scenario, AGPM is same as the scenario #2, but the gain of the turbine in thermal power plants (K_T), 25% is decreased from nominal value. Local load demands are equal to 10% and 15% for areas 1 and 2, respectively. In this scenario it is assumed that the tie-line constant (T_{12}) is increased 250%. Also, it is assumed that the load step of 0.2, 0.05, 0.1, and 0.01 are demanded by DISCOs 1, 2, 3, and 4, respectively. Based on Eq. (3) tie-line power has to be scheduled at -0.0425 pu. Dynamic response of frequency deviation and tie line power flow are shown in Fig. 9.

From Fig. 9, the proposed FP+FI+FD controller in the presence of IPFC and SMES devices has better system dynamical performance. It has to be mentioned that, effect of IPFC in tie line power flow control is stronger than SMES as its main duty, but in frequency stabilization SMES is more powerful than IPFC one, same as scenario#2. As a result, using them together may be a good choice for achieving the best performance for LFC problem. The simulation results prove that with installing IPFC and SMES, the LFC system performance is significantly enhanced by the FP+FI+FD designed in this paper based on WO algorithm for a wide range of load disturbances and possible contract scenarios under different plant parameter changes even in the presence of system physical constraints.

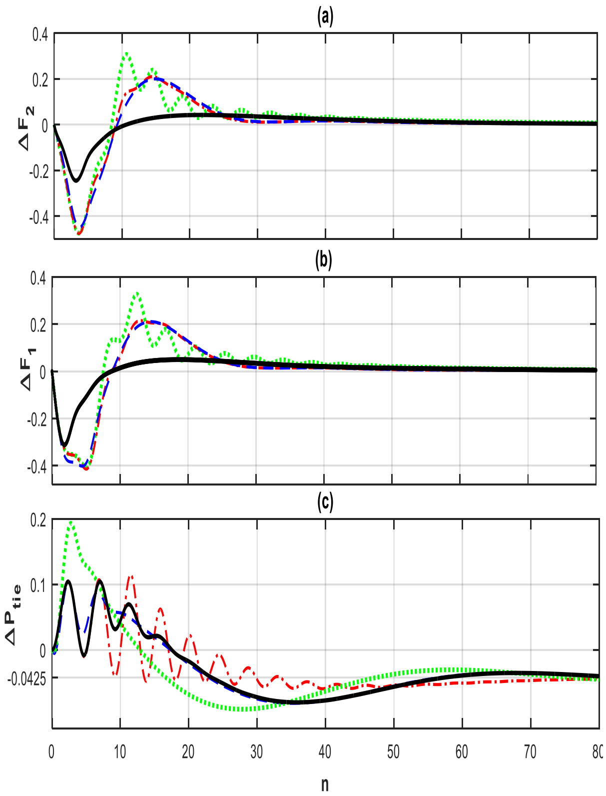


Fig. 9. Deviation of frequency and tie line power flow in scenario#2; Dotted: method (i), Dashed-Dotted: method (ii), Dashed: method (iii), Solid: method (iv)

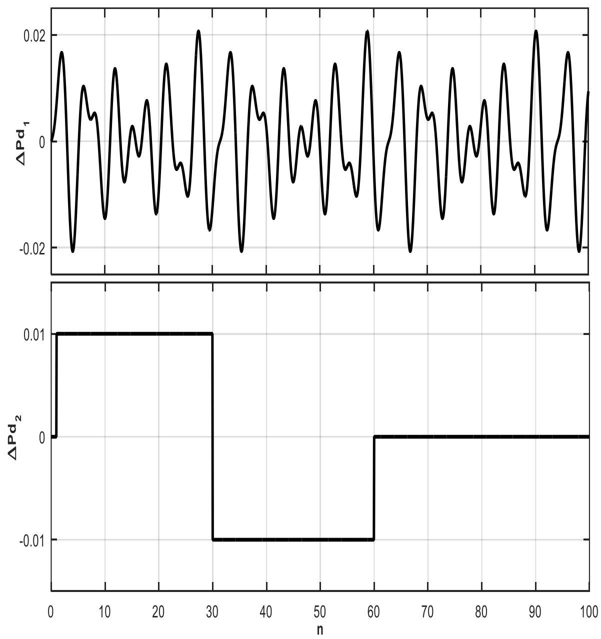


Fig. 10. Random local load patterns for scenario#3

3.4. Scenario 4

In this scenario, random load patterns shown in Fig. 10 are considered as local load demands.

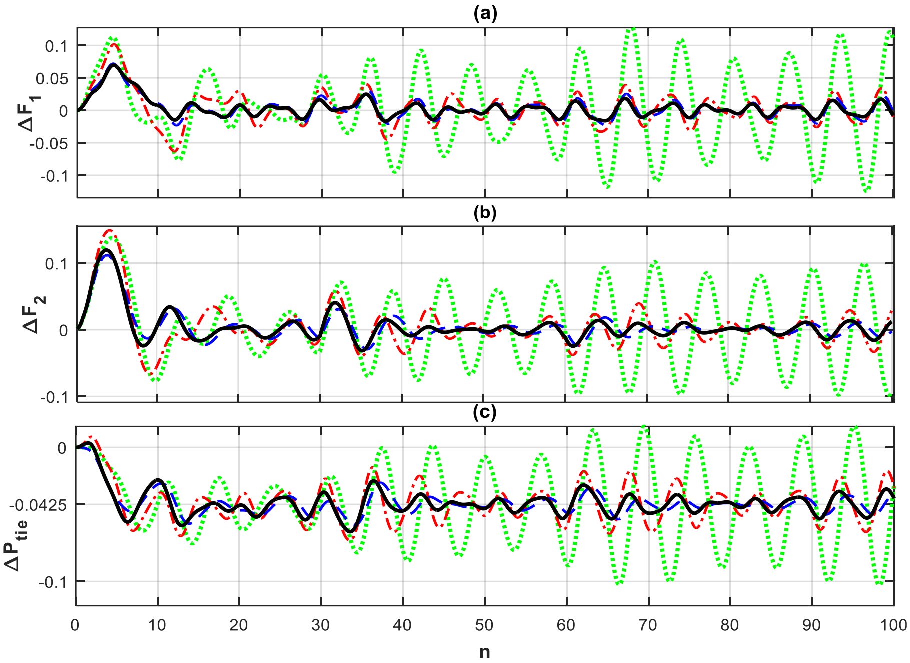


Fig. 11. Deviation of frequency and tie line power flow in scenario#2; Dotted: method (i), Dashed-Dotted: method (ii), Dashed: method (iii), Solid: method (iv)

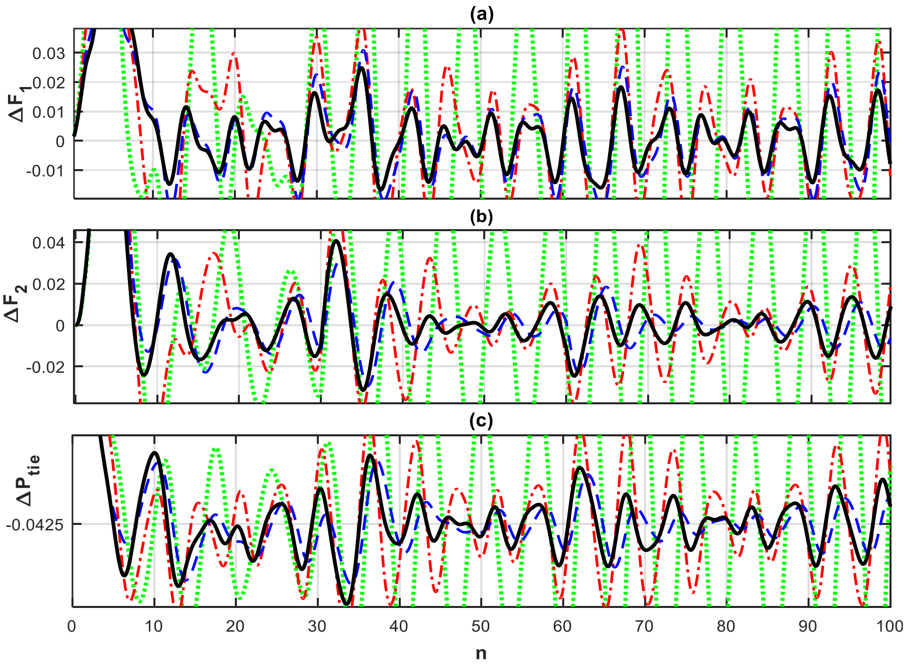


Fig. 12. Deviation of frequency and tie line power flow in scenario#2 (Zoomed); Dotted: method (i), Dashed-Dotted: method (ii), Dashed: method (iii), Solid: method (iv)

All other conditions are same as scenario#3 but instead of tie-line constant (T_{12}), loading conditions i.e.: K_P and T_P are decreased by 50%. Dynamic response of frequency deviation and tie line power flow in scenario#3 is shown in Figs. (11) and (12). Based on the simulation results, the proposed control strategy is very robust against loading condition and different challenging situations. Also, this scenario proved that, IPFC is better than SMES from the viewpoint of tie-line power flow scheduling and SMES is better than IPFC in frequency damping.

Based on simulation results, the proposed FP+FI+FD controller not only stabilizes the LFC system but has better performance than the classical fuzzy PID controller with system nonlinearities.

4. CONCLUSION

In this paper a discrete fuzzy logic based controller called

FP+FI+FD controller is designed optimally for frequency control of a multi-source power system in restructured environment. The proposed FP+FI+FD controller has a flexible structure, which merges fuzzy logic based knowledge with the conventional PID controller in a discrete form to easy implement in real time world applications. It combines the feathers of fuzzy P, fuzzy D and fuzzy integral controllers with increasing the degree of freedom to have more flexibility to achieve the desired level of robust performance, such as frequency regulation, tracking of load demand and disturbance attenuation under load fluctuation and considering physical system nonlinearities for a wide range of the plant parameters changes. In order to reduce design cost and achieve the best performance of the FP+FI+FD controller, a WOA based algorithm via minimizing a discrete objective function for a wide range of plant parameter changes including IPFC and SMES devices has been used to optimal adjust of the controller structure automatically. The proposed LFC method applied on a two-area six-unit thermal-hydro power system. At the simulation process, in the first stage, stability of the power system using FP+FI+FD controller including SMES and IPFC devices is confirmed and then using the different contracts between DISCOs/GENCOs, various local load disturbances and plant parameter variations, the performance of the proposed LFC control method is evaluated. As a result of simulation studies, from view point of the tie-line power flow, IPFC is preferable to SMES, and from the frequency view point, SMES is much better than IPFC. Then combination of them together, gives a good performance to stabilize oscillations in tie-line power flow and frequency deviations for LFC task. The simulation results prove that with installing IPFC and SMES, the LFC system performance is significantly enhanced by the FP+FI+FD controller for a wide range of load disturbances and possible contract scenarios under different plant parameter changes even in the presence of system physical constraints. The proposed optimized parallel FP+FI+FD controller with WOA algorithm successfully demonstrated robust performance as compared to the fuzzy PID controller. Moreover, due to fuzzy controller parameters increasing, it may give more flexibility to the user for achieving the desired level of system response. Finally, the smallest overshoot/undershoot and the shortest settling time and are important advantages of it.

APPENDIX

Appendix A. Two area six-unit power system data [19]: $B_1 = B_2 = 0.425$; $K_{ps1} = K_{ps2} = 120$; $T_{ps1} = T_{ps2} = 20$; $R_{TH1} = R_{TH2} = R_{TH3} = R_{TH4} = R_{HY1} = R_{HY2} = 2.4$; $T_{t1} = T_{t2} = T_{t3} = T_{t4} = 0.3$; $T_{sg1} = T_{sg2} = T_{sg3} = T_{sg4} = 0.08$; $K_{r1} = K_{r2} = K_{r3} = K_{r4} = 0.5$; $T_{r1} = T_{r2} = T_{r3} = T_{r4} = 10$; $T_{12} = 0.0433$; $T_{gh1} = T_{gh2} = 48.7$; $T_w = T_{w2} = 1$; $T_{rs1} = T_{rs2} = 0.513$; $T_{rh1} = T_{rh2} = 10$; $a_{12} = -1$;

Appendix B. SMES and IPFC data [2, 19]:
SMES: $L = 2.65$ H, $T_{dc} = 0.03$ s, $K_{SMES} = 100$ kV/unit MW, $K_{id} = 0.2$ kV/kA, $I_{d0} = 4.5$ kA.
IPFC: $T_{ipfc} = 0.01$; $K_1 = -0.3$; $K_2 = -0.2622$.

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