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Multi-Stage Fuzzy Load Frequency Control Based on Multi-objective Harmony Search Algorithm in Deregulated Environment

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ABSTRACT

A new Multi-Stage Fuzzy (MSF) controller based on Multi-objective Harmony Search Algorithm (MOHSA) is proposed in this paper to solve the Load Frequency Control (LFC) problem of power systems in deregulated environment. LFC problem are caused by load perturbations, which continuously disturb the normal operation of power system. The objectives of LFC are to mini small size the transient deviations in these variables (area frequency and tie-line power interchange) and to ensure their steady state errors to be zero. In the proposed controller, the signal is tuned online using the knowledge base and fuzzy inference. Also, to reduce the design effort and optimize the fuzzy control system, membership functions are designed automatically by the proposed MOHSA method. Obtained results from the proposed controller are compared with the results of several other LFC controllers. These comparisons demonstrate the superiority and robustness of the proposed strategy.

KEYWORDS: Load Frequency Control, Multi-Stage Controller, HSA, Deregulated Environment.

1. INTRODUCTION

Power systems are used to convert natural energy into electric power. For correct operation of a power system active power balance and reactive power balance must be maintained between the generators and loads [1-2]. Accordingly, these two balances correspond to two equilibrium points: frequency and voltage. When these two balances are broken and reset at a new level, the equilibrium points will float, while it is clear that these are required for a good quality of the electric power system during operation. Hence, control systems should be provided to cancel the effects of random load changes and keep the frequency and voltage at the standard levels [3-5].

Actually, the frequency is highly dependent on the active power and the voltage is highly dependent on the reactive power. Hence, frequency control is implemented based on the active power and voltage control is implemented based on reactive power. The former is referred to as Load Frequency Control (LFC) [6-8].

In the industry, Proportional Integral (PI) controllers have been widely used for decades as the load frequency controllers. Actually, several techniques have been proposed to design PI controllers [9], where the parameters of the PI controller are tuned using trial-and-error approach. However, it gives poor performance in the system transient response [9]. Proportional Integral Derivative (PID) method has been proposed to improve the performance of the PI controller [10]. However, the mentioned technique needs a more complex design process.

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To overcome the mentioned drawbacks, new multi-stage fuzzy PID controller is proposed in this paper to solve LFC problem. Actually, the proposed technique has two-dimensional rules and needs fewer resources to operate. Effective designs of the fuzzy controllers depends on choosing appropriate membership function, rule base inference mechanism and defuzzification [11-12]. Among these factors, tuning of the membership functions is important for the performance of the fuzzy PID controller. Probably, tuning of the membership functions by human experts is appropriate; however, such experts may not be available. To remedy this problem intelligent techniques such as particle swarm optimization (PSO) and genetic algorithm (GA) have been proposed for optimal tuning of the fuzzy LFC controller [13-14]. However, these techniques have low search ability for finding optimal solutions of complex nonlinear problems.

Harmony search algorithm (HSA) is a recently developed powerful evolutionary algorithm, inspired by the improvisation process of musicians, for solving single or multi-objective optimization problems. In the proposed technique, each musician plays a note for finding a best harmony all together. In this paper, a multi-objective HSA is proposed for optimal tuning of the membership functions of the fuzzy LFC controller. The proposed MOHSA algorithm can solve the multi-objective form of the optimization problem.

The remaining parts of the paper are organized as follows. In section 2, the LFC model is described. The proposed MOHSA algorithm is introduced in section 3. The suggested fuzzy PID controller for LFC and application of the MOHSA for its optimal tuning are presented in section 4. The proposed controller is tested on three area deregulated power system and its obtained results are compared with the results of several other LFC controllers in section 5. These comparisons reveal the effectiveness of the proposed controller for LFC. Section 6 concludes the paper.

2. LFC MODEL DESCRIPTION

Deregulated power system consists of GENCOs, TRANSCOs and DISCOs with an open access policy [15]. In the new structure, GENCOs may or may not participate in the LFC task and DISCOs have the liberty to contract with any available GENCOs in their own or other areas. Thus, it is possible to find various combinations of contracted scenarios between DISCOs and GENCOs [16-17].

The significance of an ‘augmented generation participation matrix’ (AGPM) is to express the possible contracts based on what is presented in [18]. The AGPM shows the communion factor of a GENCO in the load following contract with a DISCO [19]. The dimension of AGPM matrix in terms of rows and columns is equal the total number of GENCOs and DISCOs in the overall power system, respectively [20]. Consider that the number of GENCOs and DISCOs in area i be n_i and m_i in a large scale power system with N control areas [21]. The structure of AGPM is given by:

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

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

$$s_i = \sum_{k=1}^{i-1} n_i , z_j = \sum_{k=1}^{j-1} m_j , i, j = 2,..., N \ \& \ s_1 = z_1 = 0$$

where,

n_i = number of GENCOs in area i

m_i = number of DISCOs in area i

gpf_{ij} stands for ‘generation participation factor’ and displays the participation factor $GENCO_i$ in total load following requirement of $DISCO_j$ based on the possible contracts.

The block diagram of LFC model in a deregulated environment is presented in Fig. 1 [12]. According to this fact that there are many GENCOs for each area, ACE signal should be distributed among them due to their ACE participation factor in the LFC task and $\sum_{j=1}^{m_i} apt_{ji} = 1$. Moreover, it can be written [7]:

$$d_i = \Delta P_{Loc,j} + \Delta P_{di} \quad , \quad \Delta P_{Loc,j} = \sum_{j=1}^{m_i} (\Delta P_{Lj-i} + \Delta P_{ULj-i}) \tag{2}$$

$$\eta_i = \sum_{j=1 \,\&\, j \neq i}^{N} T_{ij} \Delta f_j \,, \quad \zeta_i = \sum_{k=1 \,\&\, k \neq i}^{N} \Delta P_{tie,ik,sch} \,.$$

$$\Delta P_{tie,ik,sch} = \sum_{j=1}^{n_i} \sum_{t=1}^{m_k} apf_{(s_l+j)(z_k+t)} \Delta P_{L(z_k+t)-k} - \sum_{t=1}^{n_k} \sum_{j=1}^{m_i} apf_{(s_k+t)(z_i+j)} \Delta P_{L(z_i+j)-i}$$

$$\Delta P_{tie,i-error} = \Delta P_{tie,i-actual} - \zeta_i \tag{3}$$

$$\rho_i = [\rho_{1i} \;\cdots\; \rho_{ki} \;\cdots\; \rho_{n_i i}] \quad , \quad \rho_{ki} = \Delta P_{m,k-i}$$

$$\Delta P_{m,k-i} = \sum_{j=1}^{z_{N+1}} gpf_{(s_i+k)j} \Delta P_{Lj-i} + apf_{ki} \sum_{j=1}^{m_i} \Delta P_{ULj-i}, k = 1,2,...,n_i$$

where, $\Delta P_{m,ki}$ = desired total power generation of a $GENCO_k$ in area *i*.

$\Delta P_{m,ki}$ must track the demand of the DISCOs in contract with it in the steady state. For each control area two GENCOs and DISCOs are considered [21]. The parameters of proposed power system are presented in [12].

3. MULTI-OBJECTIVE HARMONY SEARCH ALGORITHM

3.1. Review of HSA

The brief procedure steps of harmony search for solving optimization problems are described in five steps as:

This procedure can be described as Fig. 2.

Step 1: Arrange objective function and Equality & Inequality constraints in the following form:

$$\begin{aligned} &Minmize : \{f(x), x \in X\} \\ &s.t \\ &g(x) \geq 0 \\ &h(x) = 0 \end{aligned} \tag{4}$$

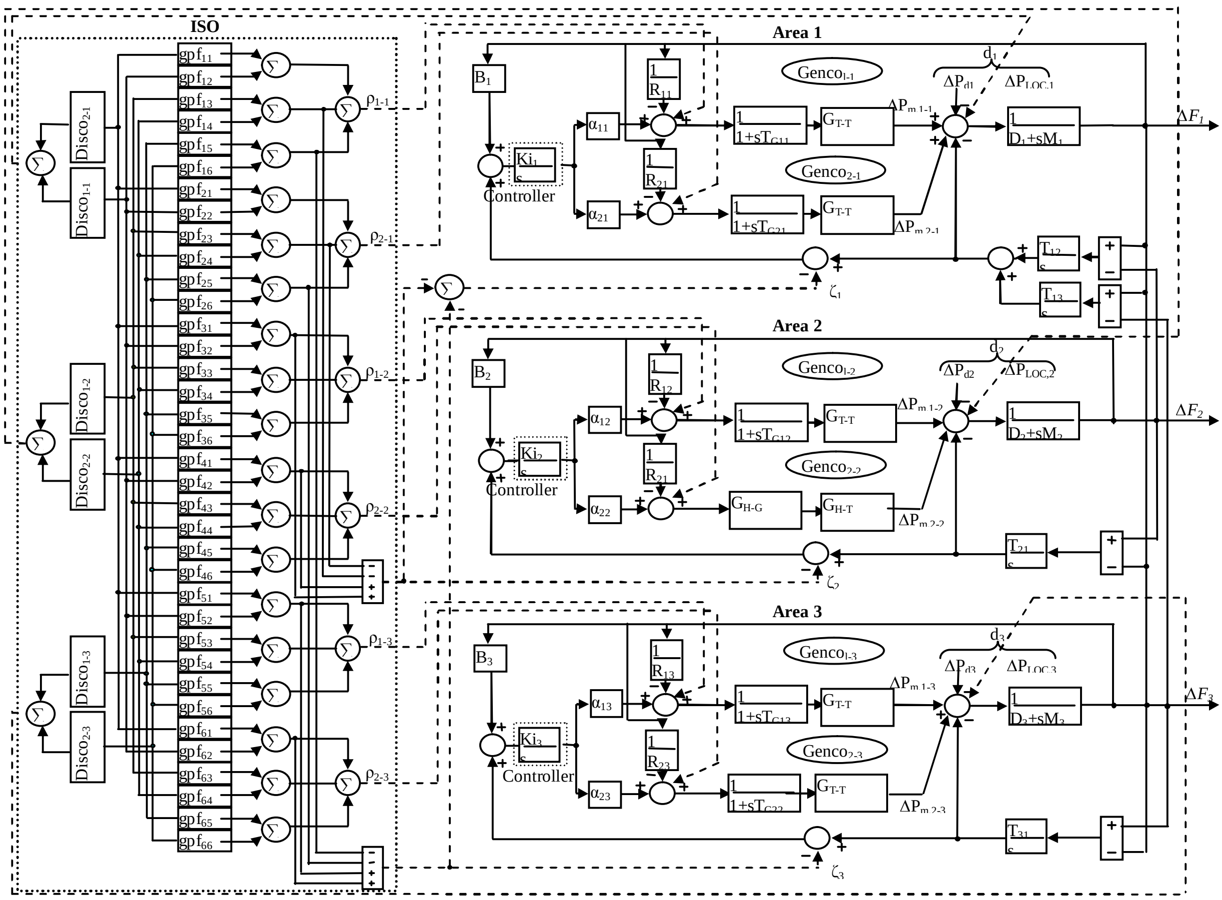


Fig. 1. Generalized LFC model in the restructured system

where, $f(x)$ is the objective function. X is the feasible set; x_i is the randomly selected parameter; $g(x)$ is the inequality constraint; $h(x)$ is the equality constraint [22].

Step 2: Initialize harmony memory (HM) [23].

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \dots & x_{N-1}^1 & x_N^1 \\ x_1^1 & x_2^2 & \dots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \dots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \dots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \frac{\Delta y}{\Delta x} \quad (5)$$

Step 3: Harmony memory initialization

The new harmony improvisation is applied in this step and consists of two stages of HMCR and PAR represented in literature as:

Step 3.1:.1 Harmony consider rated (HMCR)

$$x_i' \leftarrow \begin{Bmatrix} x_i' \in \{x_i^1, x_i^2, \dots, x_i^{HMS}\} (HMCR) \\ x_i' \in X_i\,(1-HMCR) \end{Bmatrix} \quad (6)$$

Where x_i' is new value of x_i and $HMCR$ is probability of choosing x_i' which PR means the probability function.

Step 3.2: Pitch Adjust Rate (PAR)

$$x_i' \leftarrow \begin{Bmatrix} Yes, \Pr(PAR) \\ No, \Pr(1-PAR) \end{Bmatrix} \quad (7)$$

Where, PAR is probability to shift x_i

$$x_i' \leftarrow x_i' \pm rand() \times bw \quad (8)$$

Where bw is range of x_i, rand is random number during 0-1.

Step 4: Update HM and check the stopping criterion, find value of $f(x_i')$ from substitute x_i' in (5) [24].

Step 5: To check the stopping criterion, set the NI (Number of iteration) before begins to run the simulation; HS can stop calculation instantaneously when NI is reached.

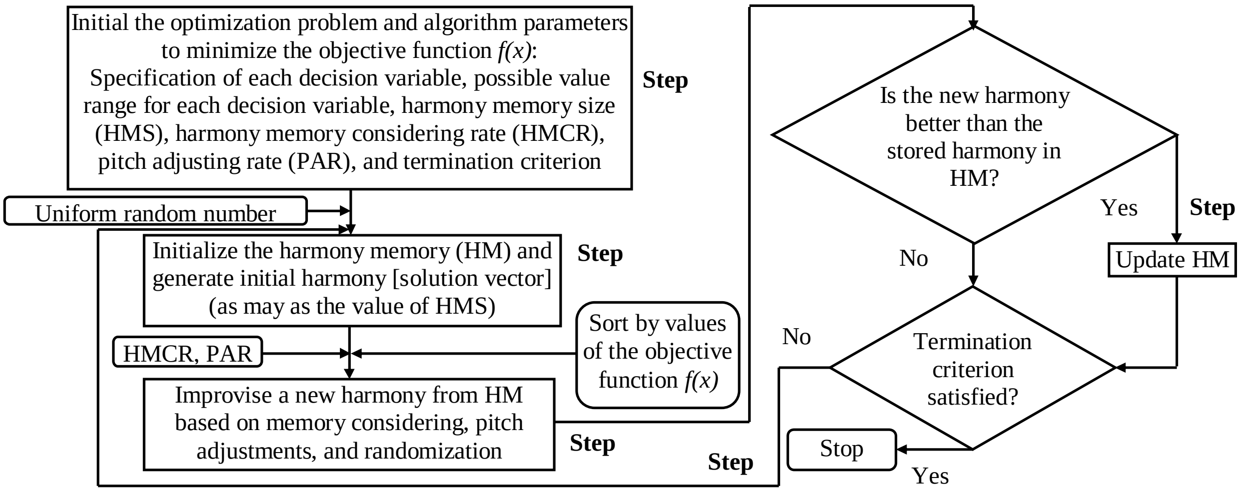


Fig. 2. Flowchart of HSA

3.2. Multi-objective strategy of harmony search algorithm

A multi-objective optimization problem always has a set of optimal solutions, for which there is no way to improve one objective value without deterioration of at least one of the other objective values. Pareto dominance concept classifies solutions as dominated or non-dominated solutions and the "best solutions" are selected from the non-dominated solutions. To sort non-dominated solutions, the first front of the non-dominated solution is assigned the highest rank and the last one is assigned the lowest rank. When comparing solutions that belong to a same front, another parameter called crowding distance is calculated for each solution. The crowding distance is a measure of how close an individual is to its neighbors. Large average crowding distance will result in better diversity in the population. In order to investigate multi-objective problems, some modifications in the HSA algorithm were made. The main steps of the MOHSA algorithm are explained in more detail.

3.3 Fuzzy mechanism

Upon having the Pareto-optimal set of non-dominated solution, the proposed approach presents one solution to the decision maker as the best compromise solutions. Due to imprecise nature of the decision maker's judgment, the i^{th} objective function is represented by a membership function μ_i defined as [26]:

$$\mu_i(p_{gi}) = \frac{f_i^{max} - f_i(p_{gi})}{f_i^{max} - f_i^{min}} \quad (9)$$

Where, f_i^{max} and f_i^{min} are the maximum and minimum values of i^{th} objective, respectively.

$$FDM_i(p_{gi}) = \begin{cases} 0 & \mu_i(p_{gi}) \le 0 \\ \mu_i(p_{gi}) & 0 < \mu_i(p_{gi}) < 1 \\ 1 & \mu_i(p_{gi}) \ge 1 \end{cases} \quad (10)$$

For each non-dominated solution k, the normalized membership function FDM^k is:

$$FDM^k = \left[\frac{\sum_{i=1}^{2} FDM_i^k(p_{gi})}{\sum_{j=1}^{M}\sum_{i=1}^{2} FDM_i^j} \right] \quad (11)$$

The best compromise solution of EED problem is the one having the maximum value of FDM^k as fuzzy decision making function where M is the total number of non-dominated solutions [25]. Then, all the solutions are arranged in descending order according to their membership function values which will guide the decision makers with a priority list of non-dominated solutions in view of the current operating conditions. Figure 3 shows the membership structure μ_c for the fuzzy logical variable signifying total fuel cost $f_i(P_{gi})$.

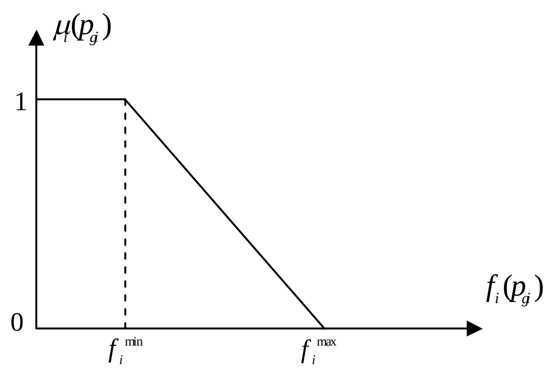


Fig. 3. Membership function of fuzzy fuel cost.

4. MULTI-STAGE FUZZY CONTROLLER

4.1. Conventional fuzzy controller

Fuzzy set theory and fuzzy logic instate the rules of a non-linear mapping. The application of fuzzy sets supplies a basis for a systematic way for the application of uncertain and indefinite models. Fuzzy set is based on a logical system called fuzzy logic controller. It is much closer in courage to human thinking and natural language than classical logical systems. Nowadays, fuzzy logic is used in approximately all sectors of industry and science. One of them is the LFC problem. Because of the complexity and multi-variable conditions of the power system, conventional control methods may not give satisfactory solutions [11]. Also, the fuzzy controller has very simple concept which consist of an input stage, a processing stage, and an output stage. The conventional structure for fuzzy controller is presented in Fig. 4.

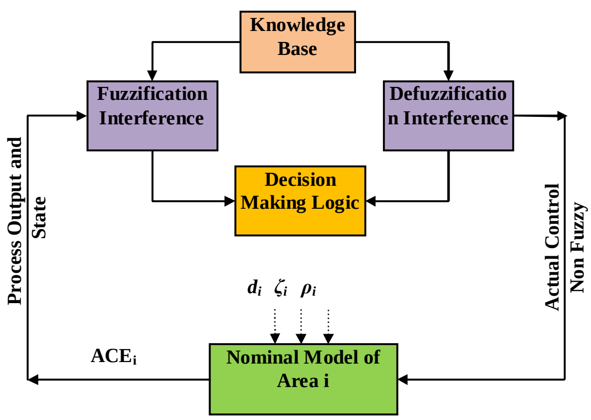


Fig. 4. The conventional fuzzy controller structure

In general, the process of fuzzy controller is defined as follows [13]:

- Fuzzification of the input variables.
- Application of the fuzzy operator (AND or OR) in the antecedent.
- Implication from the antecedent to the consequent.
- Aggregation of the consequents across the rules.
- Defuzzification.

4.2. MOHSA based on MSF controller

According to the fact that in conventional fuzzy controller finding rules needs a three dimensional information and the design process is very difficult, the multi-stage strategy is proposed in this paper [12]. In this controller, input values are converted to truth value vectors and applied to their respective rule base. It is clear that the output truth value vectors are not defuzzified to crisp values as with a single stage fuzzy logic controller. However, they are passed on to the next stage as a truth value vector input. In Fig. 5, the truth value vectors are indicated in the proposed controller strategy by darkened lines [12].

In this paper, the membership functions are described as a triangular partition with seven segments from -1 to 1. The membership function sets for this triangular is presented in [12].

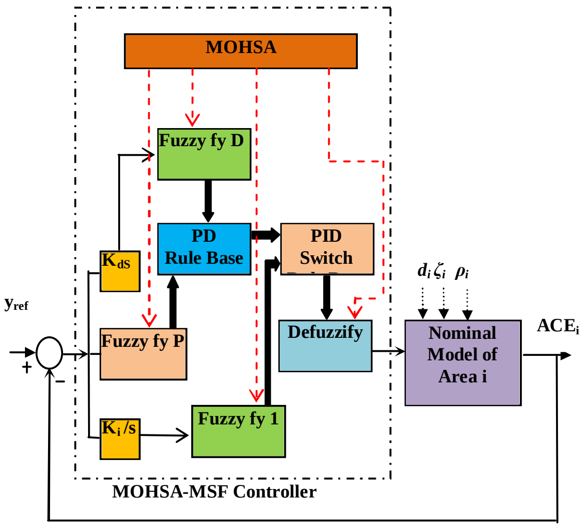


Fig. 5. Structure of the proposed controller

In this controller there are two rule bases. The first one is the PD rule base as it operates on truth vectors from the error (e) and change in error (e) inputs. And the second one is PID switch rule base while, if the PD input is in the zero fuzzy set, the PID switch rule base passes the integral error values ($\int e$) which are presented in Tables 1 and 2, respectively.

Table 1. Rule base of PD

		Δe						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	NB	NB	NB	NB	NM	NS	ZO
	NM	NB	NB	NB	NM	NS	ZO	PS
	NS	NB	NB	NM	NS	ZO	PS	PM
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NM	NS	ZO	PS	PM	PB	PB
	PM	NS	ZO	PS	PM	PB	PB	PB
	PB	ZO	PS	PM	PB	PB	PB	PB

Table 2. PID switch rule base

		PD values						
		NB	NM	NS	ZO	PS	PM	PB
$\int e$	NB	NB	NM	NS	NB	PS	PM	PB
	NM	NB	NM	NS	NM	PS	PM	PB
	NS	NB	NM	NS	NS	PS	PM	PB
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NB	NM	NS	PS	PS	PM	PB
	PM	NB	NM	NS	PM	PS	PM	PB
	PB	NB	NM	NS	PB	PS	PM	PB

This proposed strategy includes two control levels. In the first level a fuzzy network and in the second level PID controller is considered. For this purpose, the K_{Pi}, K_{Ii} and K_{Di} gains are calculated in literature as:

$$u_i = K_{Pi} ACE_i(t) + K_{Ii} \int_0^t ACE_i(t)dt + K_{Di} ACE(t)$$

In this paper two performance indices are considered simultaneously as a multi-objective optimization problem. Accordingly, Integral of the Time multiplied Absolute value of the Error (ITAE) based on *ACEi* and the Figure of Demerit (FD) based on system responses characteristic are considered as:

$$ITAE = \int_0^{10} t\left(|ACE_1(t)| + |ACE_2(t)| + |ACE_3(t)|\right)dt$$

$$FD = (OS \times 10)^2 + (US \times 4)^2 + (TS \times 0.3)^2$$

5. SIMULATION RESULTS

In this section the proposed technique is applied on a three area LFC power system in deregulated environment in various scenarios. The trend of the proposed technique is presented in Fig. 6. Also, the optimum parameters achieved by HSA for *'a'* and *'b'* parameters, presented in Table 3. All of the simulations and the achieved results are calculated with MATLAB R2010a software in ASUS computer (Intel (R) CoreTMi5-2430M CPU @ 2.40 GHz).

The applied turbine model in this paper is presented in [16]. Also, for each DISCO demands 0.1 pu MW is considered. Also, it is possible that a DISCO violates a contract by demanding more power than that of specified in the contract. This excess power should be reflected as a local load of the area but not as the contract demand and taken up by the GENCOs in the same area.

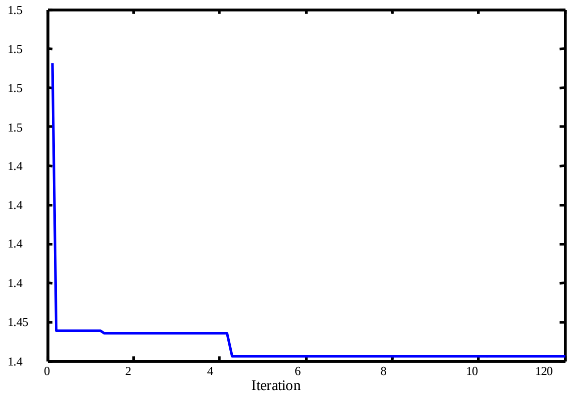


Fig. 6. Variations of fitness function

Table 3. Optimal Values of parameters a and b

Membership Function	Classic GA		Modified G		MOHSA	
	A	*B*	*a*	*b*	*a*	*b*
ACE_i	0.789	0.943	0.709	0.967	0.711	0.975
ΔACE_i	0.399	0.610	0.419	0.580	0.401	0.592
$\int ACE$	0.541	0.815	0.451	0.774	0.447	0.783
Output	0.451	0.781	0.474	0.773	0.469	0.771

To demonstrate the effectiveness of the proposed strategy, HSA is applied over three area power system through different scenarios as:

- ***Scenario 1***

In this scenario, GENCOs participate only in load following control of their areas. It is assumed that for each DISCO, a large step load of 0.1 p.u. is demanded in areas 1 and 2. Also, it is assumed that a case of *Poolco* based contracts between DISCOs and available GENCOs are simulated based on the following AGPM. Also the GENCOs of area 3 do not participate in the AGC task.

$$AGPM = \begin{bmatrix} 0.6 & 0.5 & 0 & 0 & 0 & 0 \\ 0.4 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The deviation of frequency and tie lines power flows for +25% changes and the GENCOs power changes is presented in Fig. 7. Also the desired values in this scenario are;

$$\Delta P_{M,1\text{-}1}=0.11 \text{ pu MW}$$

$$\Delta P_{M,2\text{-}1}=0.09 \text{ pu MW}$$

$$\Delta P_{M,1\text{-}2}=0.1 \text{ pu MW}$$

$$\Delta P_{M,2\text{-}2}=0.1 \text{ pu MW}$$

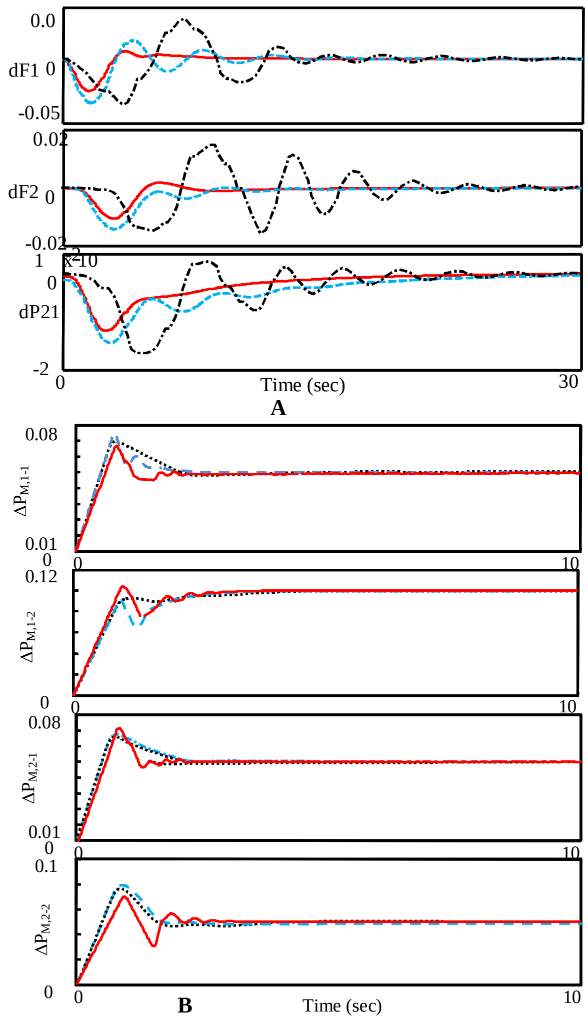


Fig. 7. a) Frequency deviation and tie line power flows, b) GENCOs power changes; Solid (MOHSA-MSF), Dashed (GAMSF) and Dotted (FPID).

• ***Scenario 2***

In this scenario, the combination of poolco and bilateral based transactionsis considered where all of the DISCOs be able to contract with any GENCO in their area. The task of all GENCOs is LFC. GENCO 1 in area 2 and GENCO 2 in area 3 only participate for performing the LFC task in their areas, while the other GENCOs track the load demand in their area and/or other areas. The AGPM for this scenario is:

$$AGPM = \begin{bmatrix} 0.25 & 0 & 0.25 & 0 & 0.5 & 0 \\ 0.5 & 0.25 & 0 & 0.25 & 0 & 0 \\ 0 & 0.5 & 0.25 & 0 & 0 & 0 \\ 0.25 & 0 & 0.5 & 0.75 & 0 & 0 \\ 0 & 0.25 & 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

In this scenario the large step load 0.1 pu MW is demanded by each DISCO in all areas. Simulation results for 25% increasing and the power changes are shown in Fig. 8. For this scenario the used information are in detail as:

$$\Delta P_{tie\,2,1,sch} = 0.025,\ \Delta P_{tie\,3,1,sch} = -0.025$$

$$\Delta P_{M,1\text{-}1}=0.1\ ,\ \Delta P_{M,1\text{-}2}= \Delta P_{M,1\text{-}3}=0.075 \ \text{pu MW}$$

$$\Delta P_{M,2\text{-}1}=0.1,\ \Delta P_{M,2\text{-}2}=0.15,\ \Delta P_{M,2\text{-}3}=0.1 \ \text{pu MW}$$

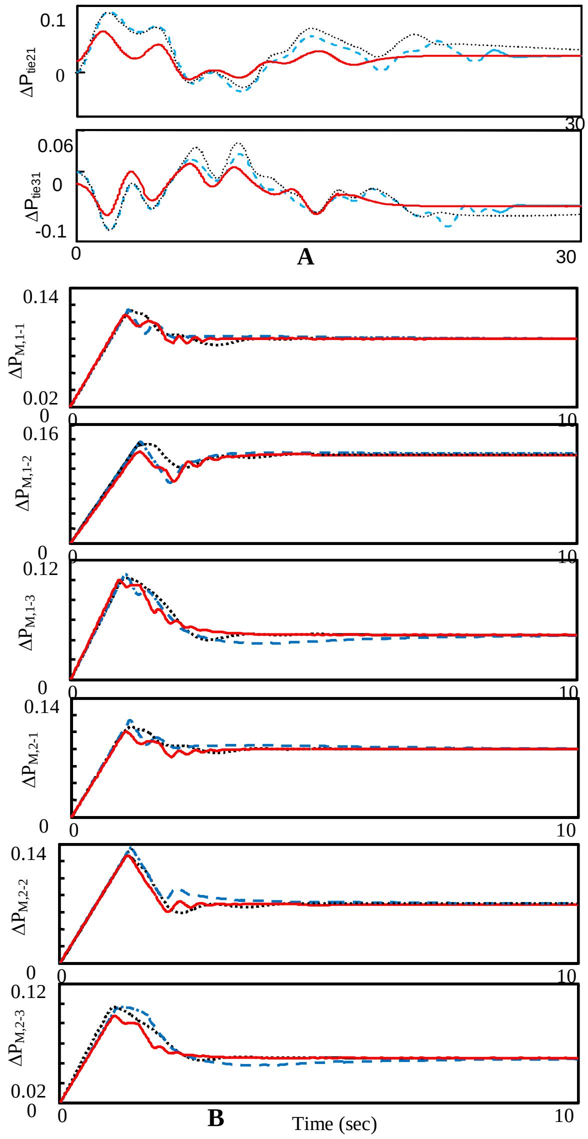


Fig. 8. a) Frequency deviation and tie line power flows, b) GENCOs power changes; Solid (MOHSA-MSF), Dashed (GAMSF) and Dotted (FPID).

• ***Scenario 3***

In this scenario the contract is assumed as scenario 2. Also, demand load for each DISCO is considered 0.1 p.u. and the load changes as a turbulence for power system is considered in Fig. 9, where;

$$-0.05 \le \Delta P_{di} \le 0.05 \text{ p.u.}$$

Testing the robustness and flexibility of the proposed technique is the aim of this scenario. For this purpose, the frequency variation in each area and deviation tile lines power flows are presented in Fig. 10.

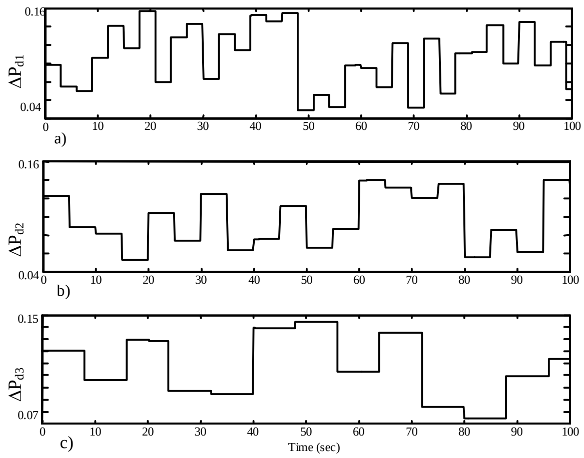
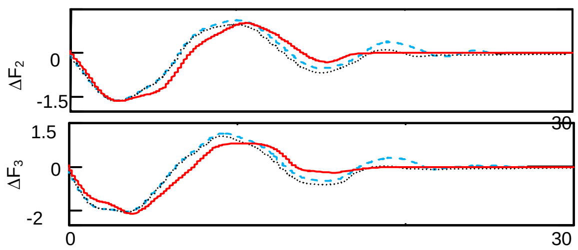


Fig. 10. The pattern of random load: a) area 1, b) area 2, c) area 3



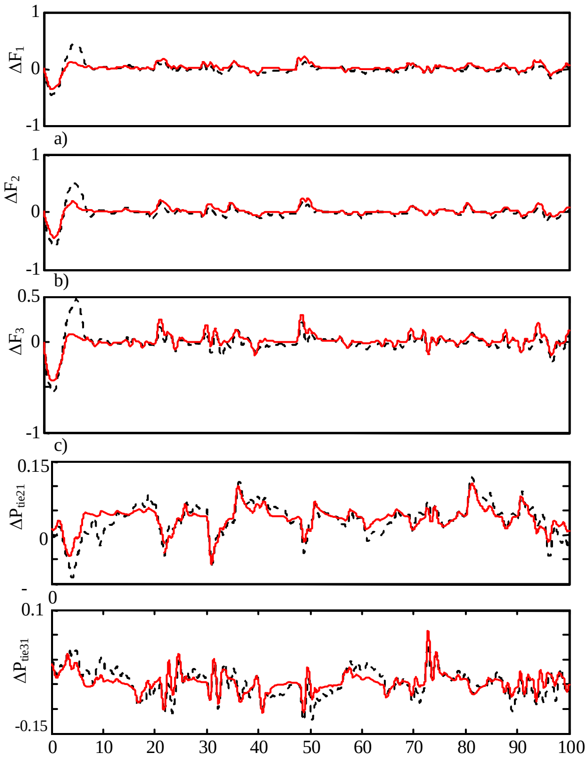


Fig. 10. Deviation tile lines power flows and he frequency variation in each area: a) area 1, b) area 2, c) area 3, Solid (MOHSA-MSF), Dashed (GAMSF)

Also the diagram results of ITAE and FD are presented in Figs. 11-13, which demonstrates the robustness of the proposed technique in LFC problem [12].

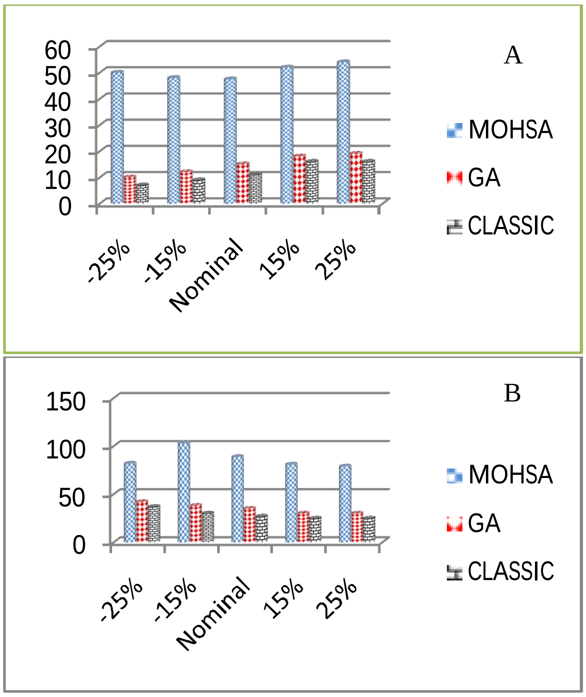


Fig. 11. Values of performance indices of scenario 1; ITAE: (A), FD: (B)

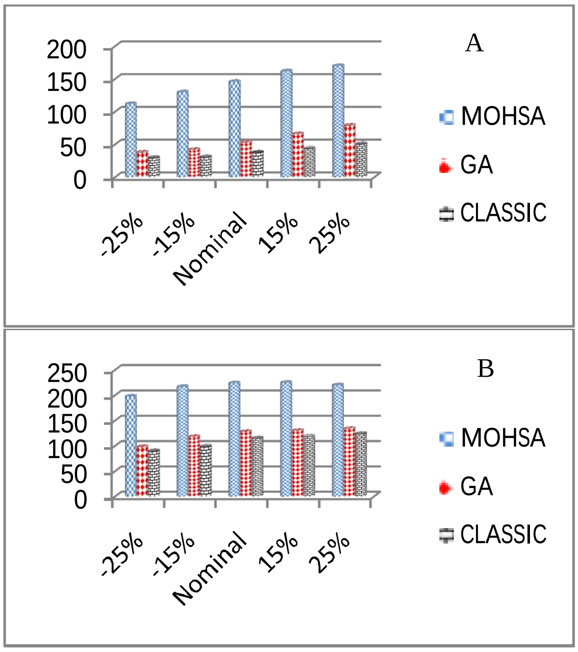


Fig. 12. Values of performance indices of scenario 2; ITAE: (A), FD: (B)

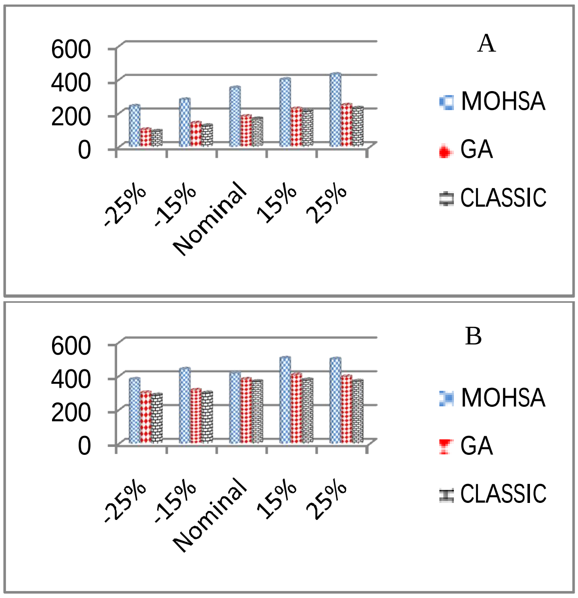


Fig. 13. Values of performance indices of scenario 3; ITAE: (A), FD: (B)

According to the simulation results it is clear that overshoot, undershoot and settling time of frequency deviation are in better situation rather than compared techniques. Also, the achieved results for ITAE and FD are lower than the multi-stage GA and fuzzy PID controllers. It means that the proposed technique minimizes the transient deviation in area frequency and tie-line power interchange of power system in deregulated environment which leads to ensure their steady state errors to be zero.

6. CONCLUSION

In this paper, a new multi-stage fuzzy controller is proposed to solve the LFC problem in power system. The presented controller is optimized by multi-objective harmony search algorithm through some performance indices. The proposed technique is considered in this system to solve the multi-objective optimization problem in a sample power system. Also, this control strategy was chosen because of the increasing complexity and changing structure of the power systems. Actually, the proposed technique has two dimensional rules, and this method needs fewer resources to operate. Also, exact tuning of membership function is really important to the proposed controller. For this purpose MOHSA is used which is new powerful algorithm for solving single or multi-objective optimization problems with real-valued or discrete parameters and is based on natural selection. The effectiveness of the proposed method is tested on a three-area restructured power system for a wide range of load demands and disturbances under different operating conditions in comparison with GA and CPID. The simulation results and numerical results of ITAE and FD demonstrate the superiority of the proposed technique.

NOMENCLATURE

F	area frequency
PTie	net tie line power flow
PT	turbine power
PV	governor valve position
PC	governor set point
ACE	area control error
α	ACE participation factor
D	deviation from nominal value
KP	subsystem equivalent gain
TP	subsystem equivalent time constant
TT	turbine time constant
TH	governor time constant
R	droop characteristic
B	frequency bias
Tij	tie line synchronizing coefficient between areas i and j
Pd	area load disturbance
PLj_i	contracted demand of Disco j in area i
PULj_i	un-contracted demand of Disco j in area i
Pm,j_i	power generation of GENCO j in area i
PLoc	total local demand
η	area interface
z	scheduled power tie line power flow deviation (Δ*Ptie*,sch.)

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