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Comparative study on the performance of many-objective and single-objective optimisation algorithms in tuning load frequency controllers of multi-area power systems

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Abstract: Load frequency control is among the most important control tasks in power systems operation. Many researchers have focused on tuning the load frequency controllers using single-objective evolutionary algorithms. To avoid the drawbacks of single-objective optimisation algorithms, in this paper, tuning the load frequency controllers is modelled as a many-objective (MO) minimization problem. This MO optimisation problem is solved using an MO optimisation algorithm with clustering-based selection. Considering the maximum value of each objective among the non-dominated solutions found by the MO optimisation algorithm, the worst solution is determined. To select one of the obtained non-dominated solutions as the controllers' parameters, a strategy based on the maximum distance from the worst solution is proposed. In order to measure the effectiveness of the proposed MO technique against several recently proposed single-objective optimisation algorithms, for tuning load frequency controllers, comparative simulation studies are carried out on two different test systems. Simulation results show that, in terms of different performance indices, the controllers designed by the proposed MO method are far superior to the controllers designed with the single-objective optimisation algorithms. Also, the presented results confirm the robustness of the controllers designed by the proposed method in case of power system parameters variations.

1 Introduction

The main duty of a power system is to continuously supply the demanded power with an acceptable quality of service. In multi-area power systems, the demand of each area can be supplied by the generating units within that area or the generating units of the other areas interconnected to that area with tie-lines. However, it should be noted that capability of tie-lines is limited and should not be overloaded. Frequency is considered as a measure of power balance. That is, when the generation is lower/higher than demand, the frequency will go under/above the nominal value. Hence, to maintain the power balance in a power system, generation should be controlled such that the frequency would not deviate beyond the specified limits and also tie-lines transferring power remains within the determined constraints. These objectives can be achieved by fine tuning the load frequency controllers. Over the last decades, a large number of methods have been proposed for tuning load frequency controllers.

Model predictive control (MPC) implemented in [1] for load frequency control (LFC) in an interconnected power system. It has been shown that while MPC uses less expensive resources, in comparison with conventional controllers, provides a better frequency response. In order to design robust load frequency controllers in multi-machine power systems, a systematic method based on maximum peak resonance specification is proposed in [2]. In [3], for LFC in power systems with a high penetration of wind generation, a linear active disturbance rejection method has been investigated. A fuzzy gain scheduling scheme has been used in [4] for the proportional-integral (PI) load frequency controllers. A control scheme based on artificial neuro-fuzzy inference was presented in [5] to optimise and update the automatic generation controllers' gains according to the load variations. In [6], the gains of a PI load frequency controller have been adaptively determined through a fuzzy system. Takagi–Sugeno fuzzy system has been proposed in [7] for LFC in a two area power system. In [8], an adaptive fuzzy logic based technique has been proposed for LFC in a multi-area power system.

Evolutionary algorithms are widely used for optimal tuning of load frequency controllers. In [9], genetic algorithm (GA) is used in order to tune the load frequency controllers of a two area non-reheat thermal power system. Actually, in [9], several performance indices were used for the PI controllers tuning, using GA. Comparative analysis on the performance of the load frequency controllers tuned by the fruit fly optimisation algorithm has been carried out in [10]. In [11], a modified form of harmony search algorithm has been proposed to solve the problem of LFC in an interconnected hydrothermal power system. In [12], a novel quasi-oppositional harmony search (QOHS) algorithm has been suggested for LFC in a multi-area deregulated power system. In [13], QOHS algorithm was implemented to tune integral-double derivative load frequency controllers in a five-area power system. QOHS has been implemented in [14] to design the fuzzy logic load frequency controllers of a hybrid isolated power system. In [15], the performance of a novel QOHS algorithm and an internal model control method for LFC were compared. For LFC in a multi-source power system, including HVDC links, differential evolution (DE) was implemented in [16]. In [17], DE was proposed for the PI and proportional-integral-derivative (PID) load frequency controllers of thermal power plants tuning in a two-area power system. Imperial competitive algorithm (ICA) was implemented in [18] to find the weighting matrices for an LQR output feedback in LFC problem. In [19], the performance of teaching-learning based optimisation (TLBO) in tuning the load frequency controllers in a multi-sources power system was compared with DE. To optimise the gains of the PID load frequency controllers of a three area power system, ICA has been used in [20]. In [21] ICA was implemented for the non-integer load frequency controllers tuning in a three area power system with reheat, non-reheat and hydraulic generating units. In [22] biogeography-based optimisation algorithm has been used for three-degree of freedom integral-derivative load frequency controllers designing.

Literature review shows that researchers have made a lot of efforts to improve the performance of load frequency controllers using novel evolutionary algorithms. It is clear that the performance of these controllers not only depends on the employed optimisation methods but also on the objective function selection method [23]. Important specifications typically used to evaluate the performance of load frequency controllers are: overshoot, settling time, and steady-state error of the frequency of different areas and tie-lines power. To design the controllers using single-objective evolutionary algorithms, different objective functions have been reported in literature including integral of time multiplied by absolute error (ITAE), integral of squared error (ISE), integral of time multiplied by squared error (ITSE) and integral of absolute error (IAE). However, it is impossible to tune the controllers in order to simultaneously satisfy all the aforementioned intrinsically contradictory specifications, considering them in a single objective function. Moreover, determination of the weight of each term in the objective function is not easy and would highly affect the solution. In [23] the load frequency controllers tuning in a two-area power system has been modelled as a multi-objective optimisation problem and solved using non-dominated sorting genetic algorithm-II (NSGA-II). Three objective functions determined in [23] are as follows: The first objective function is the sum of ITAE of the frequency deviations of two areas and tie-line power error. The second objective function accounts for damping ratio of dominant eigenvalues. The third objective function is the sum of settling time of frequency deviation of the two areas and tie-line power error. Obviously, the first and third objective functions still contain conflicting specifications that are added together. The reason behind not considering each specification as a separate objective is probably that NSGA-II does not show a good performance in solving optimisation problems with more than three objectives.

Hence, for the first time, the load frequency controllers tuning, based on a many-objective (MO) evolutionary algorithm has been proposed in this paper. For each of the above mentioned specifications, a separate objective function has been determined to be optimised. Hence, the weight determination for each objective will no longer be required and consequently its negative impact on the solution will be avoided. To solve this multi-objective optimisation problem, an evolutionary MO optimisation algorithm with clustering-based selection (EMyO/C) [24] has been implemented. In this optimisation algorithm, clustering-based diversity maintenance has been used to improve the performance of Pareto-dominance based algorithms in solving the optimisation problems with a large number of objectives. Hence, this algorithm seems to have a good performance in the load frequency controllers tuning modelled in the form of an MO optimisation problem. This optimisation algorithm yields a number of non-dominated solutions, where one has to be chosen as the final controllers' parameters. To this end, a strategy based on the maximum distance from the worst solution has been proposed. To verify the effectiveness of the proposed method, based on comparative simulation studies carried out in Matlab/Simulink environment, the performance of the proposed method has been measured against three newly proposed single-objective optimisation techniques. In the first part of simulation studies, the performance of the PID controllers tuned by the proposed MO method has been compared with the optimal PID controllers tuned using DE [16] and TLBO [19] algorithms in terms of different performance indices. Moreover, it has been shown that multi-objective optimisation algorithms such as NSGA-II do not have a good performance in the load frequency controllers tuning, modelled as an MO optimisation problem. In the second part of simulation studies, LFC in a three-area power system with PID controllers equipped with a derivative filter (PIDF) is studied. The performance of the proposed MO method in the PIDF load frequency controllers tuning for this three-area power system is compared with a novel hybrid gravitational search and pattern search algorithm (hGSA-PS) proposed in [25].

In summary, the main contributions of this paper are:

(i) To model the load frequency controllers tuning in multi-area power systems as an MO optimisation problem.
(ii) To implement EMyO/C as a newly proposed MO optimisation algorithm in order to solve the MO optimisation problem.
(iii) To propose a strategy based on the maximum distance from the worst solution to choose one of the obtained non-dominated solutions as the final solution.
(iv) To compare the performance of the proposed MO method with several single-objective optimisation methods recently suggested for tuning the load frequency controllers, based on comparative simulation studies. Moreover, to investigate the possibility of using multi-objective optimisation methods such as NSGA-II for solving this MO optimisation problem.

The remaining of this paper is organised as follows: in Section 2, the studied test systems are introduced. The proposed MO strategy for load frequency controllers tuning is introduced in Section 3. Comparative simulation results are shown in Section 4 in order to examine the effectiveness of the proposed method. Finally, the summary of achievements and conclusion are presented in Section 5.

2 Test system

In this paper, the performance of load frequency controllers in two different power systems is studied. The first power system consists of two areas with identical generating units connected together via parallel AC–DC tie-lines. In each area of this power system, electrical power is generated by thermal, hydro and gas turbine power plants. The model of this power system used for simulation studies has been shown in Fig. 1*a*. In this figure, K_{PS} and T_{PS} stand for the gain and time constant of power system, respectively. R_i is the speed regulation of the *i*th generating unit. K_G, K_H and K_T are the participation factors of gas, hydro and thermal generating units, respectively. T_{SG} is the thermal unit governor time constant and T_t is steam turbine time constant. K_r and T_r are the steam turbine reheat constant and the steam turbine reheat time constant, respectively. T_W, T_{RS}, and T_{RH} are the nominal water starting time in the penstock, governor reset time of hydro turbine and transient droop time constant of hydro turbine's governor, respectively. T_{GH} is the time constant of the main servo in hydro turbine governor. X_C and Y_C are the lead and lag time constant of the governor of the gas turbine. cg and bg are the valve positioning constant and the time constant of valve positioning of the gas turbine. T_F, T_{CR} and T_{CD} are fuel time constant of the gas turbine, combustion reaction time delay of gas turbine and compressor discharge volume-time constant of the gas turbine, respectively. The DC and AC tie-lines are modelled with first order transfer functions. T_{12} is the AC tie-line power coefficient. K_{DC} and T_{DC} are the gain and time constants of DC tile-line. More details on this model would be found in [16, 19, 26]. The parameters of this model are taken from [16].

The second test system is a three area power system with reheat thermal power plants. The model used to simulate this power system is shown in Fig. 1*b*. In this test system, power plants are modelled with more details. In fact, generation rate constraints (GRC) and governor dead band (GDB) non-linearity are considered in this model. Moreover, communication time delay in the secondary frequency control loop has been considered. The parameters of this system are taken from [25]. The areas of this power system are unequal and consequently they will have different controllers' parameters. More details on this power system would be found in [25].

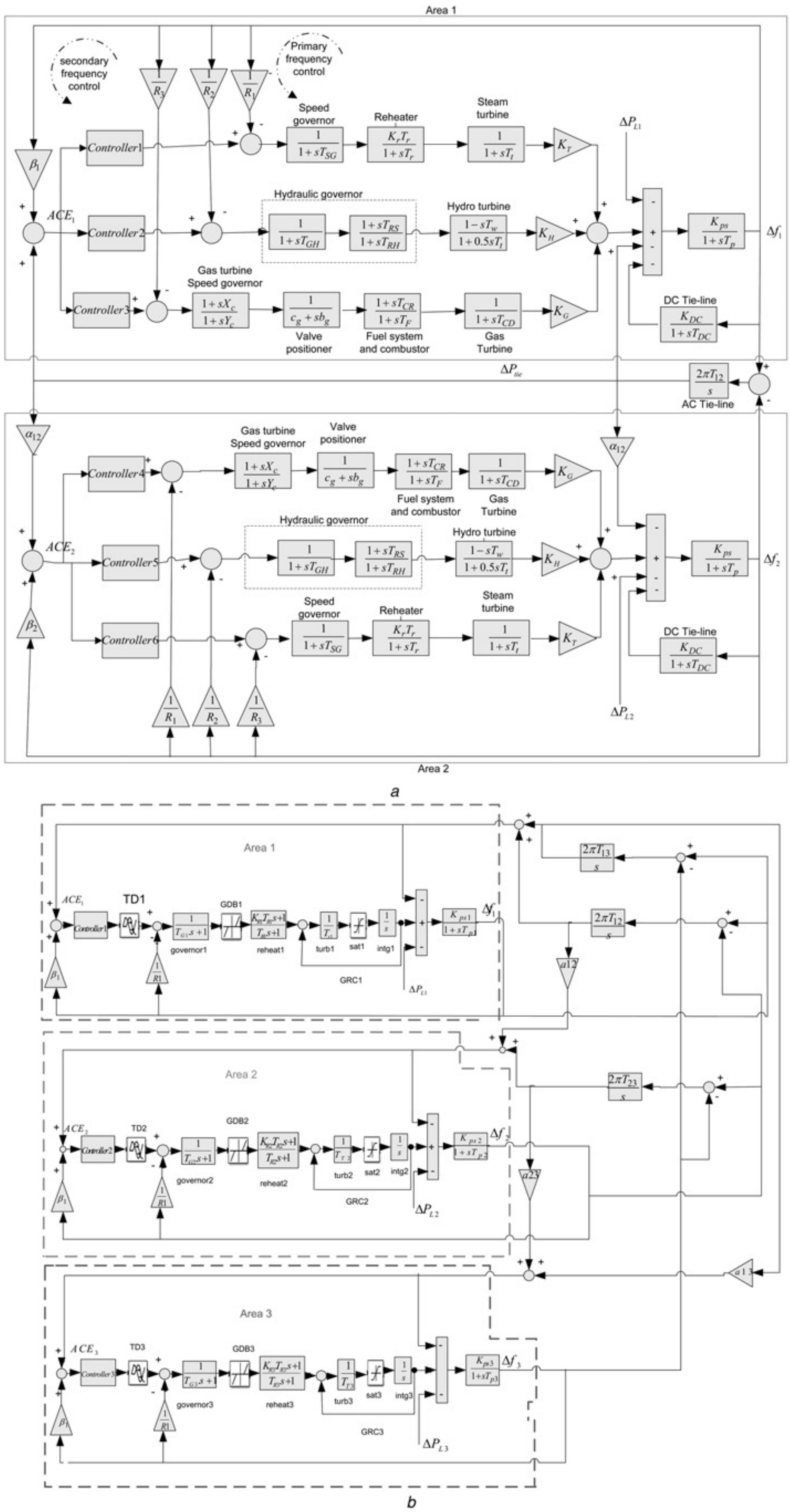

Fig. 1 *Block diagram of the studied power systems*

a Two-area power system
b Three-area power system

3 Proposed strategy for the load frequency controllers tuning

Multi-objective optimisation is a strong tool to solve problems with several conflicting objectives. These types of problems, instead of a single solution, have a set of non-dominated solution. None of the solutions in this set are better than the others in all objectives. Real world optimisation problems usually have more than few objectives. Multi-objective evolutionary algorithms have not shown a good performance in solving MO optimisation problems. Therefore, it is advised to implement MO optimisation techniques to solve these problems [27].

In this paper, the load frequency controller parameters tuning is formulated as minimisation of several objectives. These objectives would highly affect the solution. Here, for the studied two-area power system, six-objectives have been chosen to be minimised. However, tuning the load frequency controllers of the studied three-area power system will be a 12-objective minimisation problem. Due to the large number of objectives, an MO evolutionary algorithm implementing clustering-based selection [24] has been chosen to solve this optimisation problem. To select one of the non-dominated solutions, obtained by the optimisation process, as the final controllers' parameters, a strategy based on the maximum distance from the worst solution has been proposed in Section 3.1. The MO evolutionary algorithm used to obtain the non-dominated solutions has been explained in Section 3.2.

3.1 Objective functions

The purpose of LFC is to minimise the maximum deviation of frequency of all areas and tie-lines power and also return them back to zero as soon as possible. To this end, different objective functions have been proposed in literature to tune load frequency controllers using evolutionary algorithms. Most of these objective functions are based on the following criteria:

- Integral of absolute error
- Integral of square error
- Integral of time multiplied absolute error.

IAE and ISE decrease the maximum overshoot more than ITAE, on the other hand, ITAE has the advantage of decreasing settling time more than IAE and ISE [20]. In some of the previous works, weighted sum of these conflicting objectives has been used. In this paper, ITAE of deviation in frequency of each area and AC tie-lines power have been selected as the criteria to decrease their settling time. To compensate the negative effect of ITAE on maximum overshoot, the maximum overshoots of these signals has been also considered as separate objective functions. Hence, for the studied two area power system, six objective functions are determined to be minimised by EMyO/C as follows

$$\begin{aligned}
\mathrm{Obj}_1\left(K_\mathrm{p}, K_\mathrm{I}, K_\mathrm{D}\right) &= \int_0^\infty t \times |\Delta f_1|\,\mathrm{d}t \\
\mathrm{Obj}_2\left(K_\mathrm{p}, K_\mathrm{I}, K_\mathrm{D}\right) &= \int_0^\infty t \times |\Delta f_2|\,\mathrm{d}t \\
\mathrm{Obj}_3\left(K_\mathrm{p}, K_\mathrm{I}, K_\mathrm{D}\right) &= \int_0^\infty t \times |\Delta P_\mathrm{tie}|\,\mathrm{d}t \\
\mathrm{Obj}_4\left(K_\mathrm{p}, K_\mathrm{I}, K_\mathrm{D}\right) &= \max(|\Delta f_1|) \\
\mathrm{Obj}_5\left(K_\mathrm{p}, K_\mathrm{I}, K_\mathrm{D}\right) &= \max(|\Delta f_2|) \\
\mathrm{Obj}_6\left(K_\mathrm{p}, K_\mathrm{I}, K_\mathrm{D}\right) &= \max(|\Delta P_\mathrm{tie}|).
\end{aligned} \quad (1)$$

Solving this optimisation problem using EMyO/C, yields a number of non-dominated (Pareto optimal) solutions. Then, the inverse value of calculated minimum damping of the power system for each non-dominated solution would be added to the set of objectives. Using the maximum of each objective among the N non-dominated solutions, the vector of the worst objective function is determined as follows

$$\textbf{Worst\_Obj} = \left[\max_{l=1\to N} \mathrm{obj}_1^l,\ \max_{l=1\to N} \mathrm{obj}_2^l,\ \ldots,\ \max_{l=1\to N} \mathrm{obj}_m^l\right]$$

Where, obj_i^l represents the value of the ith objective in the ith non-dominated solution and m is the number of objectives. To select one of the non-dominated solutions as the final solution, the distance of each non-dominated solution from the worst objective function has been implemented

$$D^l = \sum_{i=1}^{m} \frac{\mathrm{Worst\_Obj}_i - \mathrm{obj}_i^l}{\mathrm{Worst\_Obj}_i} \quad (2)$$

The solution with the largest D will be chosen as the final solution.

The designing procedure of the load frequency controllers in the studied three-area power system is similar to what explained above; however, the number of objectives to be optimised will be 12.

3.2 MO optimisation algorithm with clustering-based selection

In the following, EMyO/C implemented for the load frequency controllers tuning, is explained [24]:

The optimisation problem is considered as follows

$$\underset{x\in\Omega\subset\mathcal{R}^n}{\mathrm{minimise}}: f(x) = \left(f_1(x), f_2(x),\ \ldots, f_m(x)\right)^\mathrm{T} \quad (3)$$

Where, m is the number of the objectives and n is the number of the decision variables. EMyO/C is an evolutionary optimisation algorithm with $(\mu + \lambda)$ selection scheme, where mating selection, variation and environmental selection are successively carried out during the generation. In EMyO/C, the initial population is generated randomly. Then, reference point, z, is initialised

$$\forall j \in \{1,\ \ldots,\ m\}:\ z_j = \min_{i=1\to\mu} f_j\left(x^i\right) \quad (4)$$

In the mating process, population members are selected from the mating pool. The variation procedure is based on the DE operator. For each member in the mating pool, two different members are selected randomly. A difference vector ($\boldsymbol{v}$) is determined using these members. Applying a polynomial mutation to the difference vector, an additional variation is formed. The constraints of the resulted difference vector are as follows

$$\boldsymbol{v}_j = \left\{\begin{array}{ll} -\delta_j & \text{if } v_j < -\delta_j \\ \delta_j & \text{if } v_j > \delta_j \\ v_j & \text{otherwise} \end{array}\right\} \quad (5)$$

Where

$$\delta_j = \frac{ub_j - lb_j}{2} : \forall j \in \{1,\ \ldots,\ n\}$$

lb_j and ub_j are the lower and upper bounds of the jth decision variable, respectively. An offspring (x') is generated from mutation of the parent individual (x)

$$x_j' = \left\{\begin{array}{ll} x_j + v_j & \text{if rand} < \mathrm{CR} \\ x_j & \text{otherwise} \end{array}\right\}: \forall j \in \{1,\ \ldots,\ n\} \quad (6)$$

To guarantee the feasibility of the offspring, it would be repaired

Table 1 Input parameters of EMyO/C

CR	Mutation distribution index	Population size, μ	Maximum generation
0.15	20	1000	50

as follows

$$x'_j = \min\left\{\max\left\{x'_j,\ lb_j\right\}ub_j\right\}: \forall j \in \{1, \ldots, n\} \quad (7)$$

The obtained offspring (x') is compared with its parent, x. If the offspring and its parent are different in at least one gene, the offspring will be evaluated and then added to the set of offspring population. Otherwise, two other members of the mating pool are chosen, and the mentioned process is repeated until an individual different from its parents is produced. This prevents evaluating and adding the offspring identical to their parents to the population set. It is worth noting that implementing the polynomial mutation makes it possible to generate new genotypes even in cases where the whole population set has converged to a single solution. Moreover, after evaluating an offspring, in case of availability of smaller objective values, the reference point components will be updated. Based on the environmental selection, non-dominated sorting procedure is carried out and, according to the rankings, a new population is selected from the multi-set of offspring and parents. When the last accepted front ($\mathcal{F}_1$) would not be completely accommodated, to select the k best individuals, the truncation procedure is carried out as follows:

(i) For all the members of $\mathcal{F}_1$, in the objective space, the Euclidean distance from the reference point is calculated.
(ii) For all the members of $\mathcal{F}_1$, the objectives are modified:
(iii) Each member of $\mathcal{F}_1$ is projected onto a unit hyperplane:

$$f_i = f_i / \sum_{j=1}^{m} f_j: \forall i \in \{1, \ldots, m\} \quad (8)$$

(iv) The projected members are used to form k clusters as follows:
First step: Initially, each member is considered as a separate cluster $c = \{c_1, c_2, \ldots, c_{|\mathcal{F}_l|}\}$.
Second step: If $|C| = k$, stop. Otherwise, go to the third step.
Third step: According to the following equation, the distance of each two clusters (d_{12}) is calculated

$$d_{12} = \frac{1}{|C_1||C_2|} \sum_{i \in C_1, j \in C_2} d(i, j) \quad (9)$$

Where, $d(i, j)$ is the Euclidean distance between members i and j.
Fourth step: The clusters pair with the smallest distance is merged. Go to the second step.

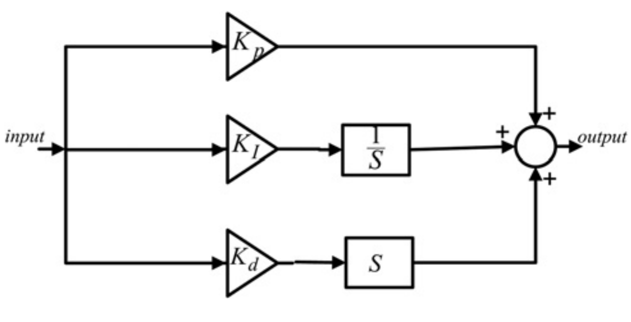

Fig. 2 *Schematic diagram of PID controller*

Table 2 Parameters of PID load frequency controllers of the two-area power system tuned by the proposed MO method

PID parameters	Thermal	Hydro	Gas
K_P	10.0000	−8.8000	10.0000
K_I	5.4774	−7.5586	10.0000
K_D	9.5170	−10.0000	10.0000

(v) A representative is chosen, from each cluster, and added to the new population set. The member of the cluster with the smallest distance to the reference point is considered as the cluster representative.

Not requiring any additional parameters makes this selection procedure completely adaptive and easy to implement. The complexity of the clustering algorithm mainly depends on the number of points in $\mathcal{F}_l$, whereas it is a polynomial in the number of objectives. This feature is very attractive to solve problems with large number of objectives.

The input parameters of EMyO/C used in this study are given in Table 1.

4 Simulation results

To show the effectiveness of the proposed strategy in the load frequency controllers tuning, several comparative simulation studies are carried out on two different power systems. The first test system consists of two areas with various generating units connected together through parallel AC–DC tie-lines. The case studies on this power system are presented in Section 4.1. The second test system is a three area power system with reheat thermal power plants. The model used to simulate this power system, considers GRC, GDB and communication time delay. Section 4.2 presents the case studies carried out on the second test system.

4.1 Two area power system

The model of the studied power system is shown in Fig. 1*a*. In these case studies, the impact of uncertainties, parameters variation and changes in the system topology on the proposed control method is investigated. The nominal frequency of the system is 60 Hz and the rated power of each area is 2000 MW. For LFC in this power system, PID controllers are chosen. The block diagram of PID controller is shown in Fig 2.

Using the procedure explained in Section 3.1, the vector of the worst objectives determined based on the non-dominated solutions, obtained by EMyO/C is the following:

WorstObj = [0.0183 0.0132 0.0269 0.0028 0.0007 0.0013 6.6528]

The PID parameters resulting to the maximum distance from the worst objective vector are given in Table 2. These parameters have been chosen as the controllers' parameters.

4.1.1 Step increase in the demand of the first area: In this case study, the performance of the PID load frequency controllers designed with different methods is evaluated in case of a 0.01 pu step increase in the demand of the first area. The results demonstrated in Fig. 3 show that the performance of the controllers tuned by NSGA-II is not better than the controllers tuned by TLBO while the performance of the controllers tuned by EMyO/C (the proposed MO method) outperforms the controllers tuned by TLBO and DE. This certifies that NSGA-II, which is a multi-objective optimisation algorithm, is not suitable for solving this MO optimisation problem.

From Figs. 3*a* and *b* it is clear that the frequency deviation in both of the areas has been decreased using the proposed method.

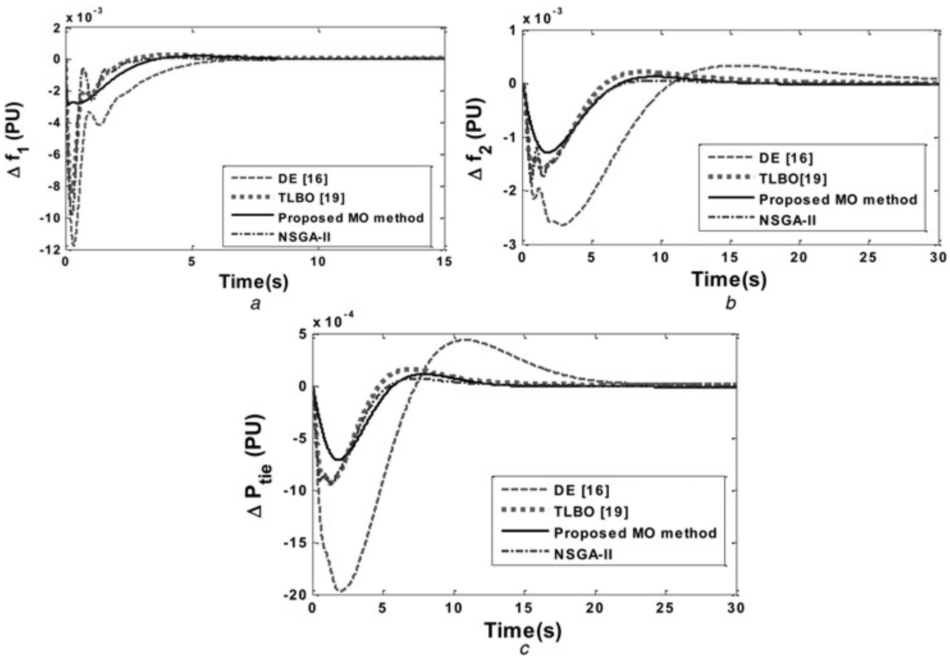

Fig. 3 *Performance of load frequency controllers in case of a 0.01 pu increase in demand of area 1*

a Frequency deviation of area 1
b Frequency deviation of area 2
c Deviation of AC tie-line power

Table 3 Different performance indices to evaluate the proposed MO method in the two-area power system

Objective functions	DE [16]	Improvement by MO method, %	TLBO [19]	Improvement by MO method, %	MO method
ITAE	0.2816	79.29	0.0680	15.01	0.0583
ITSE	2.45×10^{-4}	89.59	3.12×10^{-5}	18.26	2.55×10^{-5}
IAE	0.0488	69.26	0.0181	17.12	0.0150
ISE	1.26×10^{-4}	86.50	3.45×10^{-5}	50.72	1.70×10^{-5}
settling time of Δf_1 (s)	28.2001	73.59	9.3046	19.97	7.4462
settling time of Δf_2 (s)	28.3002	60.70	13.7326	19.01	11.1236
settling time of $\Delta P_{\rm tie}$(s)	17.8783	51.06	9.3758	6.69	8.7484

Moreover, the proposed controllers have diminished the settling time of the frequency deviation in both of the areas. Fig. 3*c* shows that the performance of the proposed controller in minimising the AC tie-line power deviation is also superior to both of the controllers proposed in [16, 19]. In Table 3 the performance of the proposed MO method in the load frequency controllers tuning, in terms of different performance indices, including ITAE, ITSE, IAE, ISE and settling times, is compared with DE [16] and TLBO [19]. Settling time is determined as the time at which the absolute value of the signal settles to <0.00001. From the results given in Table 3, the superiority of the proposed method over DE and TLBO is evident.

4.1.2 Effect of the parameters variations and change in the topology of the power system: The controllers are designed using a model of power system shown in Fig. 1*a* with estimated parameters of the system. However, due to an error in the estimation process or the low accuracy of the estimation method, the real parameters might be different from the estimated ones. Moreover, the parameters of power systems may vary as a result of a change in the operating point which might happen after large disturbances [8]. Therefore, the controllers should be robust in the case of parameters variation. In this case study, the effect of −50 to +50% changes in T_{12} on the proposed controllers' performance is studied. Connection or disconnection of some of the parallel tie-lines might bring about changes in T_{12}, which is inversely proportional to the equivalent reactance of tie-lines. The disturbance is a 0.01 pu step increase in demand of the first area. From the simulation results shown in Fig. 4, it can be found that,

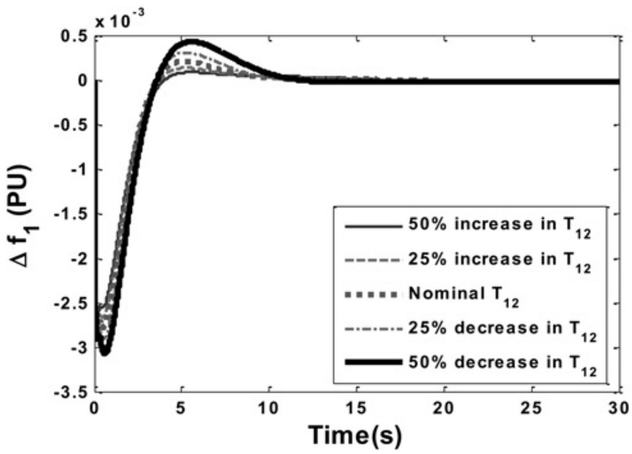

Fig. 4 *Performance of the controllers designed by the proposed MO method in case of a 0.01 pu increase in demand of area1 with change in tie-line parameter*

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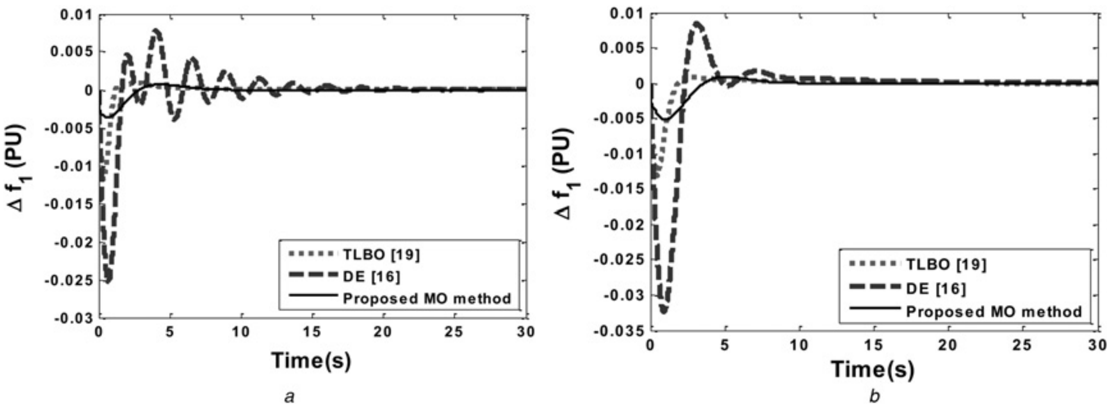

Fig. 5 *Change in the frequency of the first area for 0.01 pu increase in demand of area 1 in case of change in the topology of the system*

a HVDC link is not connected
b Two areas of the power system are separated

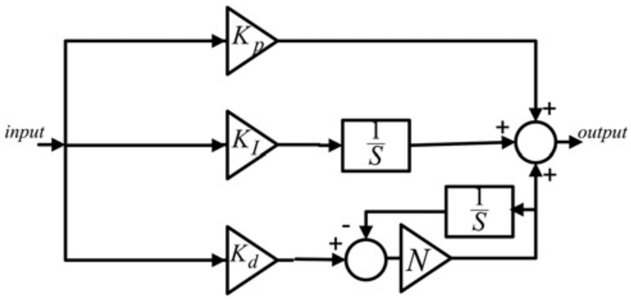

Fig. 6 *Schematic diagram of PIDF controller*

when power system parameters are different from nominal values, the controllers could show a good performance in case of disturbances and parameters variations have not had a considerable impact on frequency deviation.

Table 4 Parameters of PIDF load frequency controllers of the three-area power system tuned by the proposed MO method

PIDF parameters	Area 1	Area 2	Area 3
K_P	0.2342	− 2	− 2
K_I	−2	− 2	− 2
K_D	−0.1382	− 2	− 1.8013
N	169.1776	25.9129	300

In real power systems, it is probable that, in some operating conditions, AC and/or DC tie-lines are not connected. To avoid the necessity of retuning the controllers in such conditions, the acceptable performance of load frequency controllers should be verified.

The frequency of area 1 in case of a 0.01 pu step increase in demand of this area when the DC tie-line is not connected is shown in Fig. 5*a*. This figure shows the superiority of the proposed PID controllers over the controllers proposed in [16, 19].

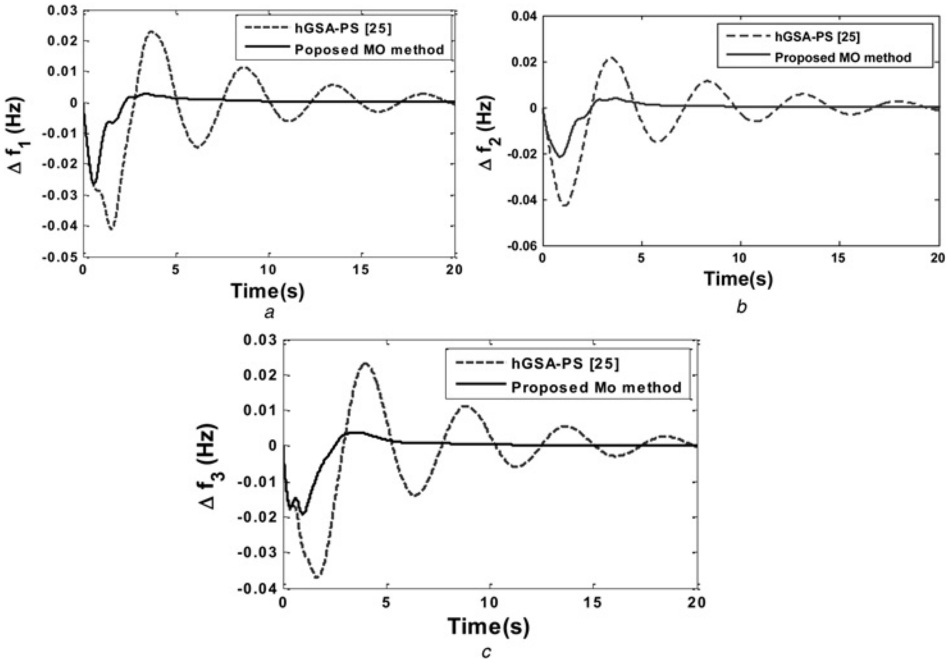

Fig. 7 *Frequency deviation of all areas in case of a 0.01 pu increase in demand of all areas*

a Frequency deviation of the first area
b Frequency deviation of the second area
c Frequency deviation of the third area

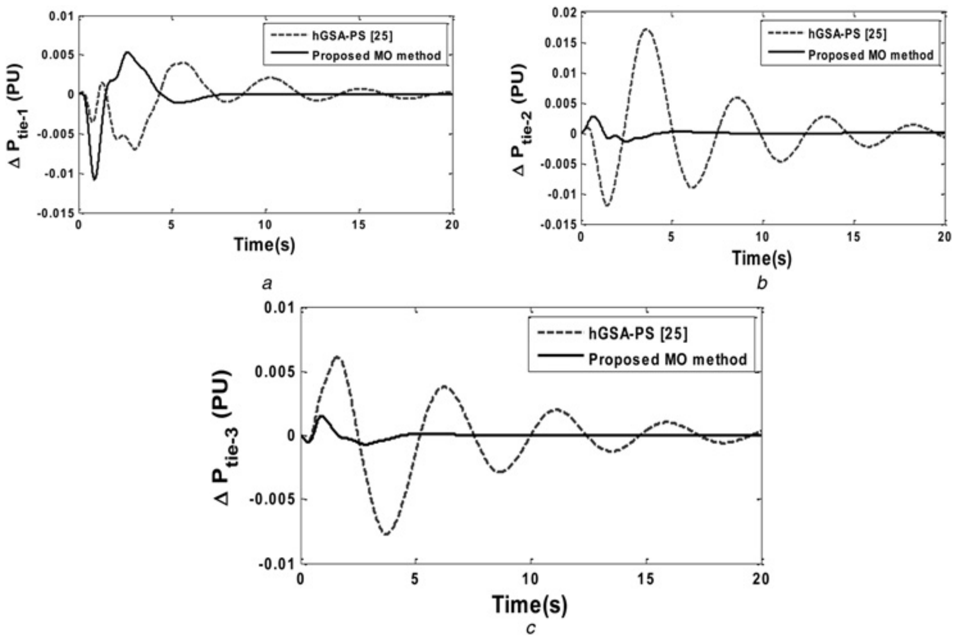

Fig. 8 *AC tie-line power deviation of all areas in case of a 0.01 pu increase in demand of all areas*

a AC tie-line power deviation of the first area
b AC tie-line power deviation of the second area
c AC tie-line power deviation of the third area

To further study the effect of change in the power system configuration on the controllers' performance, a 0.01 pu step increase has been applied to the demand of the first area when the power system is divided into two separate islands. From Fig. 5*b*, it can be found that this change in the power system configuration does not have a considerable effect on the performance of the proposed controllers and, in terms of settling time and maximum deviation, its performance is much better than the controllers proposed in [16, 19].

4.2 Three area power system

To further investigate the effectiveness of the proposed method in the load frequency controllers tuning, in this section, simulation studies are carried out on a three area power system. The model of this system simulated in Matlab/Simulink is shown in Fig. 1*b*. In this model, generation rate non-linearity, GDB and communication delay are considered. The parameters of this model are borrowed from [25]. For LFC in this power system, PIDF controller is chosen. PIDF controller is similar to the PID controller, but, as shown in Fig. 6, it has a derivative filter to diminish the effect of noise on the controller performance. The parameters of PIDF controllers designed for LFC in the three-area power system using the proposed method are given in Table 4.

The simulation results presented in Sections 4.2.1 and 4.2.2, compare the proposed method with the method proposed in [25] for PIDF load frequency controllers tuning. It should be mentioned that the studied three area power system is exactly the same as the power system studied in [25] and the parameters of the PIDF tuned by hGSA-PS has been borrowed from [25] to compare the performance of the proposed MO method with the method has been newly suggested in [25].

4.2.1 Step increase in demand of all the areas of the power system: Figs. 7*a*–*c* and 8*a*–*c* show the response of the studied three area power system to a 0.01 pu step increase in the demand of all areas. It is clear from these figures that using the PIDF controllers tuned by the proposed method not only decreases the maximum frequency deviation of all areas and tie-lines power, but also the error in this signal settles down to zero much faster than the case of implementing the controllers tuned by hGSA-PS.

Table 5 compares the performance of the proposed MO method with hGSA-PS method based on different performance indices. From the results provided in this table, it is obvious that the proposed MO method has a far better performance. Moreover, the controllers designed with the method proposed in this paper might improve the minimum damping ratio of the power system.

4.2.2 Effect of the parameters variation on controllers' performance: To evaluate the robustness of the controllers tuned by the proposed method, the response of the controllers tuned by the proposed MO method in case of change in inertia constant, T_t and T_g after occurrence of 0.01 pu disturbances in all three areas is studied in this section. Fig. 9*a* shows that the controllers tuned by the proposed MO method have an acceptable response in case of changes in inertia constant of all areas, that is, the maximum frequency deviation and the settling time of frequency deviation have not been much affected by changes in inertia constant. It can be found from Fig. 9*b* that also in case of change in T_t and T_g, the proposed controllers could preserve their good performance.

Table 5 Different performance indices to evaluate the proposed MO method in the three-area power system

Objective functions	hGSA-PS [25]	MO method	Improvement by MO method, %
ITAE	3.8245	0.2865	92.50
ITSE	0.0251	0.0010	96.01
IAE	0.5701	0.1094	80.81
ISE	0.0075	0.0009	88.00
settling time of Δf_1 (s)	38.1900	17.0900	55.25
settling time of Δf_2 (s)	33.0300	7.1200	78.44
settling time of Δf_3 (s)	38.3700	17.0600	55.53
settling time of P_{tie1} (s)	27.7500	7.3700	73.44
settling time of P_{tie2} (s)	35.5300	6.6400	81.31
settling time of P_{tie3} (s)	30.7200	6.2900	79.52
minimum damping ratio	0.1563	0.2079	33.01

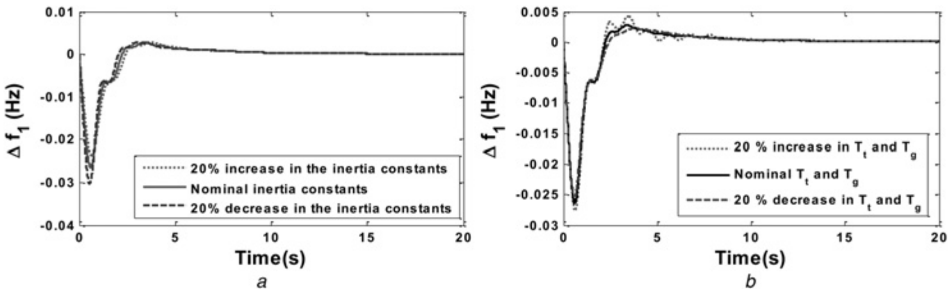

Fig. 9 *Effect of power system parameters variation on the performance of the controllers tuned by the proposed MO method*

a Inertia constants variation
b Changes in T_t and T_g

5 Conclusion

In this paper, the load frequency controllers tuning has been modelled as an MO optimisation problem. It has been shown that multi-objective optimisation algorithms such as NSGA-II are not suitable solving methods for this MO optimisation problem. Hence, EMyO/C, an MO optimisation algorithm designed for solving problems with a large number of objectives, has been used to obtain non-dominated solutions. Then, based on the obtained non-dominated solutions, the worst objective vector has been determined. Considering the distance from the worst objective, one of the non-dominated solutions has been chosen as the final solution. Comparing the performance of the proposed method, in terms of different criteria, including ITAE, ITSE, IAE and ISE, with single-objective optimisation algorithms such as DE, TLBO and hGSA-PS proves its superiority. The simulation studies on two different power systems verified the robustness of the proposed controller in case of parameters variation. It has also been shown that the performance of the proposed controller, in terms of maximum deviation and settling time, is much better than the controllers tuned by DE, TLBO and hGSA-PS methods. Moreover, the effectiveness of proposed controllers when the topology of the system is changed is confirmed.

6 References

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