Design and Implementation of FIPID Controller for LFC of Multi-unit Multi-source Linear/Non-linear Power System

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Abstract

Due to dynamic load on interconnected power system, the system frequency tends to vary. It is important to balance the active power demand and active power generation at all the time in order to minimise the deviation of frequency in interconnected power system. The control mechanism by which the demand and generation is balanced in order to minimise the frequency deviation is known as load frequency control (LFC). This article explains the load frequency control (LFC) in multi-area multi-unit interlinked linear as well as nonlinear power system by employing fuzzy logic integrated PID (FIPID) controller. A PID controller is also separately implemented for performance comparison. Every control area in the system possesses with a non-reheat thermal plant and a hydro plant. The parameters of the implemented controllers are fine-tuned by application of teaching learning based optimisation (TLBO) algorithm and modified sine cosine algorithm (MSCA) separately using integral time absolute error (ITAE) as the fitness function. Thus, four different controllers are implemented to study the LFC issues and the four controllers so implemented are TLBO-PID, MSCA-PID, TLBO-FIPID and MSCA-FIPID controllers. A comparative performance analysis is accomplished between these controllers by injecting an instantaneous load of 1.5% in area-1. At last, the robustness of the proposed MSCA-FIPID controller is examined by performing the sensitivity analysis and injecting a random step load in area-1 of the power system in presence of communication delay and system nonlinearities.

Keywords Load frequency control · Governor dead band · Area control error · Generation rate constraint · FIPID controller · Objective function · Teaching learning based optimisation · Modified sine cosine algorithm · Transient response

Introduction

Frequency control is an inevitable task in interlinked power system. It is vital to retain the frequency at a constant value to ensure the stability and power quality of a given power system. The system frequency at any point of time depends on the real power demand on the system at that time [[1]–[3]]. Practically, the real power demand is dynamic in nature and it never remains constant. Hence, it is essential to implement a suitable secondary controller for regulation of the generated power according to the active power demand

to keep the frequency within the prescribed limit and this method of balancing the load and generation is known as load frequency control (LFC).

Literature Review

The foremost work on LFC was first carried out by Cohn [[4]]. Since then, numerous research works have been performed on LFC issues as mentioned in the literature. Elgerd and Fosha [[5]] carried out an important research work on LFC issues and presented an optimum method for LFC in multi area system. Role of LFC with different viewpoints is discussed and the importance of LFC in interlinked power system is presented by Glavitsch and Stoffel [[6]]. LFC analysis in discrete mode with a new area control error is presented for a hydrothermal interlinked system [[7]]. Applications of super conducting magnetic energy storage (SMES) system and insulated-gate bipolar transistor (IGBT) based power converter is illustrated for improved performance of LFC in power system [[8]]. It

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is demonstrated that there is considerable improvement in power quality with the usage of a storage system in LFC of power system with distributed generation (DG) [[9]]. To overcome the drawbacks like exploration problem of PSO, an improved version of the algorithm called as improved PSO (IPSO) is proposed for tuning the proportional integral derivative (PID) controller for AGC in a single area power system [[10]]. A novel additional frequency control technique is proposed for AGC by the usage of Electric Vehicles (EV) along with Heat-Pump Water-Heaters (HPWH) as controllable loads to reduce the size of the Battery Energy Storage System (BESS) in wind and Photovoltaic (PV) integrated power system [[11]].

In the last five years, many important research works on AGC have been carried out by researchers. TLBO based 2-DOFPID controller is proposed for AGC of a two area multi source network and the efficacy of the proposed control approach is established over ZN, GA, BFOA, DE, and hBFOA-PSO tuned PI controller [[12]]. Optimal LFC design with distributed dynamic AGC law is presented for cost reduction under uncertainty and high load variability occurred due to large scale integration of renewable energy or distributed generation (DG) into the grid [[13]]. A combined control strategy of economic dispatch (ED) and AGC is suggested [[14]] to achieve economic operation with large scale penetration of renewable energy. A new error signal called as area injection error (AIE) is proposed instead of area control error (ACE) for AGC in [[15]]. AIE uses direct measurement of generator power levels and it is demonstrated that AIE delivers enhanced performance in comparison to ACE in presence of bias uncertainty and nonlinear characteristics of turbine-governor response. Crow search algorithm is utilised to tune the cascaded fractional order (FO) proportional derivative with filter (N) and FO-proportional-integral-derivative with filter (FOPDN-FOPIDN) for LFC in restructured power system [[16]].

Many control strategies for LFC including the application of various artificial intelligence techniques along with the conventional controllers are mentioned in the literature as discussed in the subsequent paragraphs. Proportional integral derivative (PID) controller designed by application of particle swarm optimization (PSO) algorithm is illustrated for fuzzy logic based LFC of interlinked power system [[17]]. Performance evaluation of various traditional controllers for LFC has been outlined by Nanda and Saikia [[18]]. Differential evolution (DE) and PSO algorithm are hybridised for optimal tuning of the fuzzy PID controller in interlinked power system [[19]]. Implementation of DE algorithm tuned two degree of freedom PID (2-DOFPID) controller has been illustrated for LFC of dual area interlinked thermal plant taking the effect of governor dead band

(GDB) into account [[20]]. Application of imperialist competitive algorithm (ICA) is demonstrated for fuzzy proportional integral (fuzzy PI) controller design to resolve the LFC issues of interlinked power system [[21]]. Implementation of hybrid PID-FPID controller is demonstrated for LFC of thermal plant with electric vehicle (EV) aggregators having time varying delay [[22]]. The improved version of the original firefly algorithm (FA) is developed and hybridised with Pattern Search technique to obtain hybrid Improved FA-Pattern Search (hIFA-PS) algorithm and the same is applied for optimal design of the fuzzy aided PID controller for AGC of a five area ten unit system with diverse sources of generation [[23]]. Moth Flame Optimisation (MFO) algorithm is utilised for optimal design of PI-PDF controller for AGC of two area and three area interlinked systems and it is demonstrated that its performance is better than other classical controllers such as PI, PID, PIDF controller [[24]]. Grew wolf optimisation (GWO) and pattern search (PS) algorithm are hybridised to tune the controller parameters of 2DOF-PID controller for LFC of multi-area power system and the effectiveness of the hybrid GWO-PS algorithm is proved [[25]].

Research gap and motivation

Literature review informs that the structural design of secondary controller plays an important role in determining the performance and characteristics of AGC in interlinked power system. Hence in this paper, an attempt is made to optimally design the PID and FIPID controller by employing teaching learning based optimisation (TLBO) algorithm & modified sine cosine algorithm (MSCA) and a maiden attempt is made to compare the effectiveness of MSCA and TLBO algorithm in tuning the controller parameters for LFC issues. In the recent past, many research works on LFC have been carried out to investigate the control performance of various optimally designed conventional and fuzzy logic based controllers but for the first time in this work, an effort is made to compare the control performance between TLBO designed PID, MSCA designed PID, TLBO designed FIPID and MSCA designed FIPID controllers.

Contribution and Paper Organization

The research work presented in this paper deals with the implementation of proportional integral derivative (PID) and fuzzy logic integrated PID (FIPID) controller optimally designed by two different optimisation algorithms namely TLBO and MSCA for attenuation of frequency and tie-line power in a two area interlinked system with each area

comprising of a non-reheat thermal and a hydro plant due to appearance of any sudden load perturbation.

The salient contributions of this research paper are outlined below.

- To design the PID and FIPID controller for LFC of a two area multi-source interconnected power system with system nonlinearities like generation rate constraint (GRC) and governor dead band (GDB) with communication delay by employing TLBO algorithm and MSCA.
- To investigate the dynamic performance of the above stated power system with/without system nonlinearities and communication delay by employing TLBO-PID, MSCA-PID, TLBO-FIPID and MSCA-FIPID controllers to prove (i) the dominance of the proposed MSCA-FIPID controller over others, (ii) the effectiveness of the MSCA over TLBO in tuning the controller parameters for optimal performance, (iii) PID controllers are not effective in maintaining the system stability in presence of system nonlinearities and communication delay and (iii) the controllers deliver result in an ascending order of control performance as TLBO-PID, MSCA-PID, TLBO-FIPID, MSCA-FIPID controllers with MSCA-FIPID controller delivering the best result.
- To validate the robustness of the proposed MSCA-FIPID controller against (i) parametric variations and (ii) random load application.

The research work carried out in this paper is presented in a systematic manner with different sections and is organised as follows. Section 1 presents the brief introduction on AGC issues of interlinked power system and literature review describing the relevant research works available in the literature followed by the research gap and motivation & contribution of the authors. In Sect. 2, description of the model under investigation is presented. Structural design of the various controllers and the optimisation techniques used in this research work are provided in Sect. 3. Section 4 presents the simulation results obtained under various circumstances. Finally, conclusion of the research work is outlined in Sect. 5.

System modelling

The model of the power system is sketched in Fig. 1. It comprises of two control areas which are interlinked via the tie-line. The tie-line facilitates the power interchange between the two control areas. Every area of the considered system possesses with a non-reheat thermal and a hydro plant.

The error signal $e(t)$ in LFC is known as the area control error (ACE) and ACE of every area is given by the following equations.

$$ACE_1 = B\Delta f_1 + \Delta P_{tie} \quad (1)$$

$$ACE_2 = B\Delta f_2 + \Delta P_{tie} \quad (2)$$

where, ACE_1 and ACE_2 denote area control errors of area-1 and area-2 respectively. B is the frequency bias factor, Δf_1 and Δf_2 represent the frequency changes in area-1 and area-2 respectively and ΔP_{tie} is the tie-line power change. Nominal parameters of the considered model are mentioned in Appendix-1 [[26], [27]].

In the considered model, T_h represents the time constant of hydraulic amplifier in thermal system, T_t represents the non-reheat turbine time constant of thermal plant, T_{gh1} represents the time constant of hydro governor, T_{gh2} represents the hydraulic amplifier time constant in hydro plant, T_w represents the time constant of hydro turbine, K_1 is the hydro governor gain constant, T_r is the reset time of hydraulic amplifier, B denotes the frequency bias factor, R_1 denotes the regulation of the speed governor of thermal plant, R_2 denotes the regulation of the speed governor of hydro plant, K_p is the gain constant of power system, T_p is the Time constant of power system and T_{12} is the Synchronizing coefficient.

Proposed Control Strategy

The various controllers used in this work are the PID and FIPID controller. The description of these controllers is outlined below.

Proportional integral derivative (PID) controller

PID controller is very popular controller due to its simple design and robustness. Also, it delivers better dynamic response and therefore, PID controller has always been the 1st choice of engineers since many decades. Structure of the PID controller is sketched in Fig. 2. Here, ACE is the input to the PID controller.

The output and transfer function (TF) of a PID controller are expressed as given below.

$$u(t) = A_p e(t) + A_I \int_0^t e(t) dt + A_D \frac{d}{dt} e(t) \quad (3)$$

$$G(s) = A_p + \frac{A_I}{s} + A_D s \quad (4)$$

where, A_p , A_D and A_I are the proportionality gain, derivative gain and integral gain respectively.

Fig. 1 Power system model under investigation

Fig. 2 Configuration of the PID controller

Fuzzy logic Integrated PID (FIPID) Controller

PID controller is simple in design and its implementation is easy. But PID controller suffers from the disadvantage that it does not give satisfactory performance when the system is complex, time variant and nonlinear. Also, the control performance of PID controller is unsatisfactory when the operating conditions of the system vary over a wide range.

The above drawbacks of PID controller can be resolved by the use of fuzzy logic-based controller. Fuzzy logic-based controllers can effectively maintain the system stability even if the accurate system model is not known and the system possesses with nonlinearity & varying operating conditions. The control process of fuzzy logic-based controller composed of three steps: (i) fuzzification of the variables at the input, (ii) processing of the fuzzy input variables obtained in preceding step through the fuzzy inference engine with the help of predefined membership functions and a set of fuzzy rules known as rule base, (iii) defuzzification of the output obtained in the preceding step to get the crisp value output from the controller. In this work, fuzzy logic integrated PID (FIPID) controller as shown in Fig. 3. is used as the secondary controller for LFC of the considered power system. There are two input scaling factors (K_{f1} and K_{f2}) as well as two output scaling factors (K_{f3} and K_{f4}) in the controller as shown in Fig. 3. The rule base and structure of the membership function of the proposed FIPID controller are depicted in Table 1 and Fig. 4 respectively. The rule base of

Fig. 3 Configuration of the FIPID controller

Table 1 Rule base of the FIPID controller

ACE	Δ ACE				
	NL	NS	ZR	PS	PL
NL	NL	NL	NS	NS	ZR
NS	NL	NS	NS	ZR	PS
ZR	NS	NS	ZR	PS	PS
PS	NS	ZR	PS	PS	PL
PL	ZR	PS	PS	PL	PL

Fig. 4 Structure of membership function of the FIPID controller

the FIPID controller is formulated by closely observing the system dynamics and following trial and error technique. Triangular membership function is used to enhance the computational efficiency of the controller. The two inputs to the controller are ACE and rate of change of ACE (Δ ACE).

(NL: Negative Large; NS: Negative Small; ZR: Zero; PS: Positive Small; PL: Positive Large).

Optimal Design of Controllers

The time response of any given system is greatly dependent on the parameters of the controller and therefore the parameters of controller must be properly selected by using suitable optimisation technique. Optimisation technique employs a function known as the objective function or fitness function denoted by J and then the optimisation problem is formulated by minimisation of this objective function under the constraints of lower and upper limits of the parameters to

be optimised. Various objective/fitness functions for LFC analysis are mentioned in the literature. In this work, integral time absolute error (ITAE) is selected as the objective/fitness function. ITAE is expressed by the Eq. (5) and the optimisation problem is structured as minimisation of J under the restrictions described by the Eqs. (6–7).

$$J = ITAE = \int_0^{t_r} (|\Delta f_1| + |\Delta f_2| + |\Delta P_{ie}|) dt \quad (5)$$

$$0.01 \leq A_{P,D,I} \leq 5 \quad (6)$$

$$0.01 \leq K_f \leq 5 \quad (7)$$

where, $A_{P,D,I}$ represent the proportional, derivative and integral coefficients of the PID controller as per the subscripts used at any particular instance and K_f represents the scaling factors of the FIPID controller. Various optimisation techniques have been mentioned in the literature for solution of different optimisation problems in engineering and appropriate selection of the optimisation technique is vital for a given problem otherwise it may lead to unsatisfactory result. After a careful examination of the literature, TLBO and MSCA has been chosen in this work to solve the optimisation problem so as to get the optimum parameters of the controllers.

Teaching Learning Based Optimization (TLBO)

TLBO is developed by Rao et al. in the year 2011 [[28]]. It is a metaheuristic population oriented search algorithm stimulated by the teaching and learning procedure. This algorithm simulates the effect of teacher's impact on the outcome of students in a particular class. The outcome of a student is assessed by the result or grades secured by the student. The teacher is highly educated person than the students as he shares his knowledge and experience with the students and the quality of the teacher considerably influences the output of the students. A quality teacher imparts training on the students in such a way that the outcome of the students is improved. The students can further enhance their knowledge and produce good results by interaction among themselves.

The working method of TLBO is composed of two phases. The first phase is the teacher phase which comprises of learning from the teacher whereas the second phase is the learner phase which comprises of learning by interactions between the learners or students. Various steps of TLBO algorithm are described below.

- (i) Initialisation: Initially a population with size $[NP \times D]$ is generated randomly, where NP represents the number of all learners and D represents dimension of search region denoting the number of various subjects provided.
- (ii) Teacher phase: Each teacher puts his best effort to enhance the mean class result in his assigned subject. The teacher is considered to be the highly educated person as he trains the learners and therefore, he is taken to be the ultimately best learner. Hence, the best solution (X_{best}) is found out and designated as teacher. The average or mean value of the marks secured in each subject by different students is computed as:

$$M_d = [m_1, m_2, \dots, m_D] \quad (8)$$

The difference between mean value of the grades in a given subject and the grade of respective teacher is determined by:

$$M_{diff} = rand \times [X_{best} - T_F M_d] \quad (9)$$

where, T_F denotes the teaching factor, $rand$ denotes a random positive real number of value less than 1. The value of T_F may be 1 or 2 and randomly decided using the equations given below.

$$T_F = round(1 + rand) \quad (10)$$

where, $rand$ denotes a positive real random number of value less than 1.

The existing population gets updated by using the following relation.

$$X_{new} = M_{diff} + X \quad (11)$$

Elements of X_{new} are retained if $J(X_{i,new}) < J(X_i)$, else elements of X_{new} are replaced by corresponding elements of X . Here, J denotes the objective function as defined by Eq. (5).

- (iii) Learner phase: A learner arbitrarily selects another learner and tries to enrich his knowledge by mutual interactions with the other learner. The learner enhances his knowledge through mutual interaction when the other learner is more knowledgeable than him. The procedure of learning in this step is described by the equations given below.

$$X_{new} = rand(X_i - X_j) + X_i, \text{ if } J(X_i) < J(X_j) \quad (12)$$

Otherwise,

$$X_{new} = rand(X_j - X_i) + X_j \quad (13)$$

where, X_i and X_j are two arbitrarily selected learners and $i \neq j$.

If X_{new} performs better then it is kept. Step (ii) and (iii) will be repeated till the stopping criterion is arrived and lastly the elements with best solution is retained.

Sine Cosine Algorithm (SCA)

Sine Cosine Algorithm (SCA) was developed by Mirjalili in the year 2016 [[29]] and it is a population based search algorithm. It has the characteristics of faster convergence and has the capability of avoiding local optima. It provides random solutions oscillating towards or outwards the best solution and is designed on a model formulated by trigonometric sine and cosine functions. The process followed by SCA consists of initialisation, evaluation and updation. The various steps of this algorithm are outlined below.

- (i) Initialisation: During this step, an initial population of size $[NP \times D]$ with initial position (x_i) is randomly generated. Here, NP denotes the number of particles and D denotes the dimension of search space.
- (ii) Evaluation: During this step, the power system model is run and the fitness function of each particle $J(x_i)$ as defined by Eq. (5) is evaluated to select the solution with best fitness function. The solution corresponding to best fitness function is treated as the best solution (P_i) obtained so far and is denoted as the target solution.
- (iii) Updation: During this step, the initial position of each particle is updated by using the following equation.

$$x_i^{new} = \begin{cases} x_i + r_1 \times \sin(r_2) \times |r_3 P_i - x_i| & \text{for } r_4 < 0.5 \\ x_i + r_1 \times \cos(r_2) \times |r_3 P_i - x_i| & \text{for } r_4 \geq 0.5 \end{cases} \quad (14)$$

Where, r_2 is a random number between 0 and 2π specifying the travelling distance towards or outwards the destination, r_3 and r_4 are random numbers in between 0 and 1 where r_3 is used to carry a random weight for P_i and r_4 is used to facilitate the switching between sine and cosine functions. To have the balance between exploration and exploitation for finding the promising search space to reach global optimum, r_1 is adaptively updated by the following equation.

$$r_1 = a - \frac{t}{T} \quad (15)$$

Table 2 Optimal controller parameters

TLBO-PID controller parameters implented in thermal plant of area-1 and area-2				TLBO-PID controller parameters implmented in hydro plant of area-1 and area-2			
A_{P1}	A_{f1}	A_{D1}		A_{P2}	A_{f2}	A_{D2}	
4.1805	5.0000	1.2410		2.2847	4.4670	1.0396	
MSCA-PID controller parameters implmented in thermal plant of area-1 and area-2				MSCA-PID controller parameters implmented in hydro plant of area-1 and area-2			
A_{P1}	A_{f1}	A_{D1}		A_{P2}	A_{f2}	A_{D2}	
3.5631	4.2684	1.5701		2.5379	1.9517	2.2238	
TLBO-FIPID controller parameters implmented in thermal plant of area-1 and area-2				TLBO-FIPID controller parameters implmented in hydro plant of area-1 and area-2			
K_{f1}	K_{f2}	K_{f3}	K_{f4}	K_{f5}	K_{f6}	K_{f7}	K_{f8}
5.0000	5.0000	1.9776	4.9917	0.7015	4.8856	0.0100	0.0100
MSCA-FIPID controller parameters implmented in thermal plant of area-1 and area-2				MSCA-FIPID controller parameters implmented in hydro plant of area-1 and area-2			
K_{f1}	K_{f2}	K_{f3}	K_{f4}	K_{f5}	K_{f6}	K_{f7}	K_{f8}
4.9986	5.0000	2.0763	5.0000	4.8978	0.2253	2.9337	0.1902

where, t denotes the present iteration and T denotes the maximum iteration and a is a constant.

After updating the initial position of the particles, the fitness function of each newly produced particles $J(x_i^{new})$ are evaluated and compared with the fitness function $J(x_i)$ of previous particles. Based upon the above comparison, the initial positions of each particle are updated and steps (ii) and (iii) are repeated till the maximum iteration is reached to retain the best solution.

Modified Sine Cosine Algorithm (MSCA)

Modified Sine Cosine Algorithm [[22]] is a newly developed algorithm obtained by incorporating a mutation phase in the SCA as described below. During the phase of mutation, some elements of the newly produced solution are replaced by random numbers generated in a specified range. As an

example, let the solution produced following the updation step of SCA for $NP = 7$ and $D = 8$ is as follows:

$$x^{new} = \begin{bmatrix} 1.8481 & 1.7367 & 0.9008 & 0.2469 & 0.0053 & 0.3580 & 0.2947 & 0.9390 \\ 0.7735 & 1.3888 & 1.6952 & 1.7837 & 1.1173 & 1.8720 & 1.6877 & 0.3486 \\ 0.9163 & 1.3265 & 1.4454 & 1.3260 & 0.3341 & 1.8672 & 1.4512 & 0.9556 \\ 1.1386 & 0.8067 & 0.6475 & 1.7327 & 0.9983 & 1.6914 & 0.1153 & 1.2162 \\ 0.1330 & 1.0040 & 0.1891 & 1.6621 & 0.9673 & 0.7829 & 0.9533 & 0.3870 \\ 1.1641 & 0.9356 & 1.1243 & 1.9466 & 0.8332 & 0.2530 & 1.0492 & 0.9118 \\ 0.6325 & 0.6658 & 1.8952 & 1.9080 & 1.4634 & 1.6196 & 1.9831 & 0.8563 \end{bmatrix} \quad (16)$$

For incorporating the mutation phase, 7 random integers are produced in the range [1, 8]. Let the numbers so produced are:

$$R_i = [2344618] \quad (17)$$

Fig. 5 Variation of the frequency in area-1 **Fig. 6** Variation of the frequency in area-2

Fig. 7 Variation of the tie-line power

Hence, 2nd element of 1st solution (i.e., 2nd element of 1st row of x^{new}), 3rd element of 2nd solution, 4th element of 3rd solution, 4th element of 4th solution, 6th element of 5th solution, 1st element of 6th solution and 8th element of 7th solution are replaced by random numbers produced within a specified range [0,2]. Let the numbers so produced are:

$$R_1 = [0.56521.96510.70911.29930.38001.90740.7142] \quad (18)$$

Hence, the new solution is obtained as follows:

$$x^{new1} = \begin{bmatrix} 1.8481 & 0.5652 & 0.9008 & 0.2469 & 0.0053 & 0.3580 & 0.2947 & 0.9390 \\ 0.7735 & 1.3888 & 1.9651 & 1.7837 & 1.1173 & 1.8720 & 1.6877 & 0.3486 \\ 0.9163 & 1.3265 & 1.4454 & 0.7091 & 0.3341 & 1.8672 & 1.4512 & 0.9556 \\ 1.1386 & 0.8067 & 0.6658 & 1.2993 & 0.9983 & 1.6914 & 0.1153 & 1.2162 \\ 0.1330 & 1.0040 & 0.1891 & 1.6621 & 0.9673 & 0.3800 & 0.9533 & 0.3870 \\ 1.9074 & 0.9356 & 1.1243 & 1.9466 & 0.8332 & 0.2530 & 1.0492 & 0.9118 \\ 0.6325 & 0.6658 & 1.8952 & 1.9080 & 1.4634 & 1.6196 & 1.9831 & 0.7142 \end{bmatrix} \quad (19)$$

Now, the fitness function corresponding to each solution are evaluated and the best performing solutions are considered for the next iteration. For example, let the

Fig. 8 Variation of area-1 frequency with the MSCA-FIPID control parameters obtained in case-I

fitness function evaluated for each solution of x^{new} and x^{new1} are as follows:

$$fit^{new} = [0.21830.82180.92310.85100.79220.35910.4439] \quad (20)$$

$$fit^{new2} = [0.83860.91940.37680.56730.11130.42390.5771] \quad (21)$$

So, the 1st, 2nd, 6th and 7th solution are to be taken from x^{new} whereas the 3rd, 4th and 5th solutions are to be taken from x^{new1} for the next iteration as a result of which the solution that will take part in the next iteration is as follows:

$$\begin{bmatrix} 1.8481 & 1.7367 & 0.9008 & 0.2469 & 0.0053 & 0.3580 & 0.2947 & 0.9390 \\ 0.7735 & 1.3888 & 1.6952 & 1.7837 & 1.1173 & 1.8720 & 1.6877 & 0.3486 \\ 0.9163 & 1.3265 & 1.4454 & 0.7091 & 0.3341 & 1.8672 & 1.4512 & 0.9556 \\ 1.1386 & 0.8067 & 0.6475 & 1.2993 & 0.9983 & 1.6914 & 0.1153 & 1.2162 \\ 0.1330 & 1.0040 & 0.1891 & 1.6621 & 0.9673 & 0.3800 & 0.9533 & 0.3870 \\ 1.1641 & 0.9356 & 1.1243 & 1.9466 & 0.8332 & 0.2530 & 1.0492 & 0.9118 \\ 0.6325 & 0.6658 & 1.8952 & 1.9080 & 1.4634 & 1.6196 & 1.9831 & 0.8563 \end{bmatrix} \quad (22)$$

Table 3 Transient performance specifications due to application of 1.5% SLP in area-1

Controllers	Δf_1			Δf_1			ΔP_{tie}			ITAE
	$U_{sh} \times 10^{-3}$	$O_{sh} \times 10^{-3}$	T_S	$U_{sh} \times 10^{-3}$	$O_{sh} \times 10^{-3}$	T_S	$U_{sh} \times 10^{-3}$	$O_{sh} \times 10^{-3}$	T_S	
TLBO-PID	-9.4639	0.3335	2.9082	-3.4039	0.0592	2.5456	-1.1188	0.0318	2.1142	0.0233
MSCA-PID	-9.1757	0.2320	2.6456	-3.1542	0.0446	3.0102	-1.0429	0.0262	2.5262	0.0206
TLBO-FIPID	-6.8016	0.0097	2.5407	-2.2520	0.0062	4.7743	-0.7196	0.0028	3.2779	0.0167
MSCA-FIPID	-6.5518	0.0033	2.5607	-2.0492	0.0047	4.4015	-0.6931	0.0010	3.1257	0.0155

Fig. 9 Variation of area-2 frequency with the MSCA-FIPID controller parameters obtained in case-I

The process is repeated till the maximum iteration is reached and finally, the best solution is retained.

Result Analysis

Figure 1 shows the scrutinised power system model. Each parameters of this system are depicted in Appendix-1. The considered system is modelled and simulated in the MATLAB and Simulink environment. The controllers employed for LFC analysis of considered power system are PID and FIPID controllers. TLBO and MSCA algorithm

Fig. 10 Variation of tie-line power with the MSCA-FIPID controller parameters obtained in case-I

are scripted in the .m file and integrated with the considered model for optimal tuning of the controllers. In each case, the numbers of population is taken as 100 (i.e. $NP = 100$) and numbers of iteration taken in one run is 20 with a total of 10 runs.

In the first step, the transient performance analysis of the scrutinized system is carried out by employing TLBO optimized PID (TLBO-PID) controller, MSCA optimized PID (MSCA-PID) controller, TLBO optimized FIPID (TLBO-FIPID) controller and MSCA optimized FIPID (MSCA-FIPID) controller independently considering two cases: (i) excluding the effect of GRC, GDB and communication delay and (ii) including the effect of communication delay as well as system nonlinearities like GRC and GDB. In the next step, the robustness of the proposed MSCA-FIPID controller is examined by (i) accomplishing the sensitivity analysis and (ii) injecting a random step load in area-1. In the following discussion and figures, U_{sh} represents the maximum undershoot, O_{sh} represents the maximum overshoot and (T_s) represents the settling time of frequency and tie-line power deviations.

Transient Performance Analysis

Case-I (Power system model without GDB, GRC and communication delay)

As stated above, in the first instance, the power system model considered for investigation of LFC performance is a linear model without any communication delay and thus, the model does not include GDB and GRC. A step load perturbation (SLP) of 1.5% is imparted in area-1 and the transient system response is examined independently by implementation of TLBO tuned PID and FIPID as well as MSCA tuned PID and FIPID controllers. The tuned parameters of all the controllers obtained by the injection of 1.5% SLP in area-1 are given in Table 2. The transient response of tie-line power oscillations and frequency oscillations with the above stated controllers are depicted in Figs. 5, 6 and 7 and the corresponding transient response specifications with ITAE values for a simulation period of 20 s are depicted in Table 3.

By careful examination of ITAE value, transient performance specifications given in Table 3 and transient responses shown in Fig. 5, 6 and 7, it can be inferred that the MSCA optimised PID controller delivers superior performance than the TLBO designed PID controller, TLBO optimised FIPID controller delivers superior performance than the MSCA optimised PID controller and finally, MSCA optimised FIPID controller delivers superior performance than all other controllers.

Comparing the performance of TLBO-PID and MSCA-PID controller, it is observed from Table 3 and Figs. 5, 6 and 7 that apart from settling time (T_s) for Δf_2 and ΔP_{tie} , rest

Table 4 Optimal controller parameters

TLBO-PID controller parameters implented in thermal plant of area-1 and area-2				TLBO-PID controller parameters implmented in hydro plant of area-1 and area-2			
A_{P1}	A_{I1}	A_{D1}		A_{P2}	A_{I2}	A_{D2}	
1.8022	3.1049	0.7739		0.0100	2.0527	1.9548	
MSCA-PID controller parameters implmented in thermal plant of area-1 and area-2				MSCA-PID controller parameters implmented in hydro plant of area-1 and area-2			
A_{P1}	A_{I1}	A_{D1}		A_{P2}	A_{I2}	A_{D2}	
1.6073	3.3959	0.8579		1.3423	1.3084	0.2232	
TLBO-FIPID controller parameters implmented in thermal plant of area-1 and area-2				TLBO-FIPID controller parameters implmented in hydro plant of area-1 and area-2			
K_{f1}	K_{f2}	K_{f3}	K_{f4}	K_{f5}	K_{f6}	K_{f7}	K_{f8}
4.7052	2.4025	2.7481	4.7978	4.7074	1.6948	0.0100	3.5141
MSCA-FIPID controller parameters implmented in thermal plant of area-1 and area-2				MSCA-FIPID controller parameters implmented in hydro plant of area-1 and area-2			
K_{f1}	K_{f2}	K_{f3}	K_{f4}	K_{f5}	K_{f6}	K_{f7}	K_{f8}
5.0000	3.0842	3.0142	5.0000	4.4488	2.5816	0.1117	5.0000

Fig. 11 Variation of area-1 frequency with retuned controller parameters **Fig. 12** Variation of area-2 frequency with retuned controller parameters

of the performance specifications for MSCA-PID controller has least value. MSCA-PID controller exhibits less undershoot (U_{sh}) and less overshoot (O_{sh}) for Δf_1 , Δf_2 and ΔP_{tie} as compared to the TLBO-PID controller. Further, MSCA-PID controller gives least ITAE value as compared to TLBO-PID controller. Hence, it is concluded that the control performance of MSCA-PID controller is better than the TLBO-PID controller.

Similarly comparing the performance of MSCA-PID and TLBO-FIPID controller, it is evident from Table 3 and Figs. 5, 6 and 7 that apart from settling time (T_s) for Δf_2 and ΔP_{tie} , rest of the performance specifications for TLBO-FIPID controller has least value. TLBO-FIPID controller exhibits less undershoot (U_{sh}) and less overshoot (O_{sh}) for Δf_1 , Δf_2 and ΔP_{tie} as compared to the MSCA-PID controller. Further, TLBO-FIPID controller gives least ITAE value as

compared to MSCA-PID controller. Hence, it is inferred that the control performance of TLBO-FIPID controller is better than the MSCA-PID controller.

Further, comparing the performance of MSCA-FIPID and TLBO-FIPID controller, it is witnessed from Table 3 and Figs. 5, 6 and 7 that apart from settling time (T_s) for Δf_1 , rest of the performance specifications for MSCA-FIPID controller has least value. MSCA-FIPID controller exhibits less undershoot (U_{sh}) and less overshoot (O_{sh}) for Δf_1 , Δf_2 and ΔP_{tie} as well as least settling time (T_s) for Δf_2 and ΔP_{tie} as compared to the TLBO-FIPID controller. Further, MSCA-FIPID controller gives least ITAE value as compared to TLBO-FIPID controller. Hence, it is evidenced that the control performance of MSCA-FIPID controller is better than the TLBO-FIPID controller.

Fig. 13 Variation of tie-line power with retuned controller parameters

In view of the above facts, it is evident that (i) FIPID controllers delivers superior control performance than the PID controllers, (ii) MSCA is more effective in delivering the better result than the TLBO algorithm and (iii) the controller can be arranged sequentially in a descending order of control performance as MSCA-FIPID controller, TLBO-FIPID controller, MSCA-PID controller and TLBO-PID controller with MSCA-FIPID controller delivering the best performance amongst all other controllers.

Case-II (Power system model considering GDB, GRC and communication delay)

In this case, the power system model includes communication delay as well as system nonlinearities like GDB and GRC. Inclusion of communication delay, GDB and GRC makes the system practical and realistic one. In case of thermal and hydropower plants, the increase or decrease in power generation according to the load takes place at a specified rate and therefore, the rate of power generation is limited by the generation rate constraint (GRC). Governor dead band (GDB) of a plant is given by the continual speed change within which there is no change in valve position. The system response becomes oscillatory in nature

Fig. 14 Convergence Profile of MSCA and TLBO

because of the effect of GDB. Further, communication delay in interlinked power system is inevitable due to incessant complexity of modern power system. In the present work, GRC for thermal plant has been taken as $\pm 5\%/min$ and GRC for hydro plant has been taken as $270\%/min$ for increasing the generation and $360\%/min$ for decreasing the generation. Further, a GDB with limiting value of 0.036 and a communication delay of 50 ms have been considered in this work. As observed from Fig. 8, 9 and 10, it is obvious that with the existing controller parameters of the MSCA-FIPID controller (best performing controller in Case-I) as obtained in Case-I and depicted in Table 2, the system becomes unstable. Hence, the controller parameters of the controllers are retuned again by employing the MSCA and TLBO algorithm with injection of 1.5% SLP in area-1 and the optimal gains of the controller in this case are depicted in Table 4. The transient response of tie-line power oscillations and frequency oscillations with retuned parameters of the controllers are depicted in Fig. 11, 12 and 13 and the corresponding transient response specifications with ITAE values for a simulation time of 40 s are depicted in Table 5.

By careful examination of ITAE value and transient performance specifications given in Table 5 and transient responses shown in Fig. 11, 12 and 13, it can be inferred that

Table 5 Transient performance specifications due to application of 1.5% SLP in area-1

Controllers	Δf_1			Δf_2			ΔP_{tie}			ITAE
	$U_{sh} \times 10^{-3}$	$O_{sh} \times 10^{-3}$	T_s	$U_{sh} \times 10^{-3}$	$O_{sh} \times 10^{-3}$	T_s	$U_{sh} \times 10^{-3}$	$O_{sh} \times 10^{-3}$	T_s	
TLBO-PID	-31.5181	2.6646	40.0000	-27.5544	3.6087	17.3215	-6.7533	1.5836	5.8343	0.5228
MSCA-PID	-27.3395	2.5235	39.5316	-26.2741	5.6943	11.1157	-6.0091	2.2427	7.7607	0.3054
TLBO-FIPID	-23.4570	0.7974	13.4006	-20.5713	0.1230	6.6368	-4.9789	0.4785	6.1894	0.2851
MSCA-FIPID	-17.1849	0.4405	22.8565	-18.4162	0.3639	10.0383	-3.4987	0.8684	3.1918	0.2554

Fig. 15 Frequency oscillations in area-1 due to variation of T_h

Fig. 18 Frequency oscillations in area-1 due to variation of T_t

Fig. 16 Frequency oscillations in area-2 due to variation of T_h

Fig. 19 Frequency oscillations in area-2 due to variation of T_t

Fig. 17 Tie-line power oscillations due to variation of T_h

in this case also, the MSCA optimised PID controller delivers superior performance than the TLBO designed PID controller, TLBO optimised FIPID controller delivers superior performance than the MSCA optimised PID controller and finally, MSCA optimised FIPID controller delivers superior performance than all other controllers.

It is evident from Table 5 and Figs. 11, 12 and 13 that the PID controllers are not capable of maintaining the system stability in an effective manner due to system nonlinearity and communication delay even if the controller parameters are retuned. It is because the settling time (T_s) for frequency deviation in area-1 (Δf_1) is very large. However, the MSCA-PID controller effectively damps out the frequency oscillation in area-1 in 39.5316 s just before the end of simulation period but the TLBO-PID controller fails to damp out the

Fig. 20 Tie-line power oscillations due to variation of T_t

Fig. 22 Frequency oscillations in area-2 due to variation of T_{gh1}

Fig. 21 Frequency oscillations in area-1 due to variation of T_{gh1}

Fig. 23 Tie-line power oscillations due to variation of T_{gh1}

oscillation of frequency in area-1 till the end of the simulation period as a result of which the ITAE value given by the TLBO-PID controller is very large. The MSCA-PID controller manages to maintain the system stability but the control performance is not so good. Comparing the control performance of these two controllers, it can be concluded that the MSCA-PID controller dominates over the TLBO-PID controller.

On the other hand, FIPID controllers are able to deal with the system nonlinearities and communication delay in an effective manner as evidenced from Table 5 and Figs. 11, 12 and 13. Comparing the control performance of MSCA-FIPID and TLBO-FIPID controllers, it is observed that the MSCA-FIPID controller gives least value for five

performance specification parameters out of the nine performance specification parameters. Most importantly, the MSCA-FIPID controller gives least undershoot for $\Delta f_1, \Delta f_2$ and ΔP_{tie} and yet it gives the least ITAE value as compared to TLBO-FIPID controller. Hence, the MSCA-FIPID controller is considered to be superior than the TLBO-FIPID controller.

Comparing the transient performance of case-I and case-II, it is obvious that the transient performance of the system in case-II is degraded as compared to case-I and it is quite natural due to the presence of system nonlinearities and time delay in case-II. But, as discussed earlier in section Sect. 3.2, the FIPID controller exhibits satisfactory performance and is

Fig. 24 Frequency oscillations in area-1 due to variation of T_{gh2}

Fig. 26 Tie-line power oscillations due to variation of T_{gh2}

Fig. 25 Frequency oscillations in area-2 due to variation of T_{gh2}

Fig. 27 Frequency oscillations in area-1 due to variation of T_w

able to maintain the system stability even with the inclusion of time delay and nonlinearities like GDB and GRC in the system.

Considering the facts presented above, it is concluded that (i) the transient performance of the system degrades if there is nonlinearity and communication delay in the system (ii) the PID controllers are not suitable for nonlinear power systems involving communication delay, (ii) MSCA is more effective in delivering the better result than the TLBO algorithm and (iii) the controller can be arranged sequentially in a descending order of control performance as MSCA-FIPID controller, TLBO-FIPID controller, MSCA-PID

controller and TLBO-PID controller with MSCA-FIPID controller delivering the best performance amongst all other controllers.

The convergence profile of TLBO-PID and MSCA-PID controller as shown in Fig. 14 shows the faster convergence capability of MSCA as compared to TLBO algorithm.

Robustness Analysis

The robustness of the proposed MSCA-FIPID controller is examined by (i) performing sensitivity analysis and (ii) injecting a random step load in area-1.

Fig. 28 Frequency oscillations in area-2 due to variation of T_w

Fig. 29 Tie-line power oscillations due to variation of T_w

Sensitivity Analysis

Sensitivity analysis is accomplished to verify the robustness of the proposed MSCA-FIPID controller as discussed below. The different time constants of the system are varied over a range of -10% to +10% of the nominal value to perform the sensitivity analysis. The time constants varied are T_h , T_r , T_{gh1} , T_{gh2} and T_w . The frequency deviations in both areas (Δf_1 & Δf_2) along with the tie-line power oscillation (ΔP_{tie}) due to variations of different time constants are depicted in Fig. 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28 and 29. It is obvious from Fig. 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28 and 29 that the controller is proficient in retaining

Fig. 30 Random step load injected in area-1 and corresponding frequency variation in area-1

Fig. 31 Random step load injected in area-1 and corresponding frequency variation in area-2

the system stability even with the variations of different time constants over a wide range.

Injection of random step load

The robustness of the MSCA-FIPID controller is further verified by injection of a random step load in area-1 with the existing controller parameters as depicted in Table 4. The injected random step load varies in the range of [0.02 -0.02] p.u. The nature of the random load (ΔP_{L1}) and the corresponding frequency deviations in both areas (Δf_1 & Δf_2) along with the tie-line power variation (ΔP_{tie}) are depicted

Fig. 32 Random step load injected in area-1 and corresponding tie-line power variation

in Fig. 30, 31 and 32. It is evident from Fig. 30, 31 and 32 that the controller is proficient in retaining the system stability even under the application of random load varied over a wide range.

Conclusion

In this work, a dual area interlinked power system consisting of a non-reheat thermal and a hydro generating plant in each area is modelled and PID controller alongwith FIPID controller are implemented for load frequency control. A step load of 1.5% is applied in area-1 and all the parameters of the controllers are optimised by employing MSCA and TLBO algorithm. As such, the dynamic performance of the system is investigated with four different controllers namely TLBO-PID, MSCA-PID, TLBO-FIPID and MSCA-FIPID controllers. Firstly, the performance of the scrutinised system is investigated with all the controllers independently by neglecting the effect of communication delay as well as the effect of nonlinearities like GDB and GRC. Secondly, the effect of communication delay as well as the effect of GDB and GRC are considered and the performance of the system is investigated by implementation of all the controllers independently. In both the cases, SLP of 1.5% is applied in area-1. In both the cases, it is observed that the MSCA-FIPID controller delivers superior control performance as compared to other controllers. Further it is observed that in both the cases, MSCA optimised PID controller delivers superior performance than the TLBO designed PID controller and TLBO optimised FIPID controller delivers superior performance than the MSCA optimised PID controller. It is also demonstrated that the MSCA is more effective than the TLBO algorithm

in tuning the controller parameters and thus provides better results. In the second case, it is observed that the FIPID controllers effectively maintains the system stability in presence of communication delay and system nonlinearities whereas the PID controllers perform poor in maintaining the system stability when system nonlinearities and communication delay are included in the model. Finally, robustness of the proposed MSCA-FIPID controller is verified by accomplishing the sensitivity analysis and injecting a randomly varying step load in area-1.

Appendix-1

Nominal parameters of the system under investigation are given below.

$$\begin{aligned}
 T_h &= 0.08s, T_t = 0.3s, T_{gh1} = 48.7, T_{gh2} = 0.513s, T_w = 1.0s, K_1 \\
 &= 1.0s, T_r = 5.0s, B = 0.425p.u.MW/HzR_1 \\
 &= 2Hz/p.u., R_2 = 2.4Hz/p.Kp = 100Hz/p.u., Tp \\
 &= 20s, T_{12} = 0.0707p.u.
 \end{aligned}$$

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