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Improved PSO based automatic generation control of multi-source nonlinear power systems interconnected by AC/DC links

A.K. Barisal1* and Somanath Mishra2

Abstract: This paper presents the automatic generation control of two unequal areas with diverse power generation sources like thermal, hydro, wind and diesel power plants. Three evolutionary optimization techniques named Bacteria Foraging algorithm, Particle swarm optimization (PSO) and Improved PSO (IPSO) have been applied to tune the PID controller for the power system under study. In this paper an improved PSO technique with a constraint treatment mechanism called dynamic search space squeezing strategy is devised to accelerate the optimization process in the PSO algorithm. The dynamic performance of two unequal areas with diverse sources is investigated by the proposed IPSO optimized PID controller and with the cost function integral of time multiplied absolute error (ITAE) considering 1% step load perturbation in either one of the control areas and all of the control areas. It is found that significant improvement in the system dynamic performance is achieved by considering parallel AC/DC lines in comparison to only AC tie lines between control areas. The parameters obtained with proposed approach at nominal condition need not be required to reset while performing sensitivity analysis. Also, satisfactory system performance is obtained when subjected to random load perturbation.

ABOUT THE AUTHORS

A.K. Barisal received his BE in Electrical Engineering from UCE Burla (now VSSUT Burla), his ME (Eng.) in Power systems from BESU, Howrah (Now IIEST) and his PhD (Eng.) from Jadavpur University, Kolkata. He has published over 100 articles in different journals and conferences. His research interests include economic load dispatch, Hydrothermal Scheduling and soft computing applications to power system operation and control. He is currently working as an Associate Professor in the Department of Electrical Engineering, Veer Surendra Sai University of Technology, Burla, Odisha, India.

Somanath Mishra received her BTech in electrical engineering from Seemanta Engineering College, Mayurbhanj, Odisha and his MTech in power system engineering from C. V. Raman College of Engineering, Bhubaneswar. He is currently pursuing his PhD in VSSUT Burla, Odisha, India. His current research interests include generation, load frequency control of multi area power systems with non-conventional energy sources using intelligent techniques.

PUBLIC INTEREST STATEMENT

The world’s power systems are facing a structural change including liberalization of markets, technological advancement, integration of alternative energy sources and restrictions in carbon emissions to combat climate change and to save the Nation. The integration of intermittent energy sources in the power system create manifold challenges and problems, which are yet to be resolved. The purpose of automatic generation control is to maintain a desired operating level characterized by nominal frequency, voltage profile and power flows in power systems. The major benefit of DC link is its inherent ability for fault-current blocking, which is not possible with synchronous AC links. In addition, HVDC can effectively support the surrounding AC systems during transient fault conditions and it acts as safeguard against cascading disturbances in power system. Furthermore, the addition of wind and diesel units to meet the peak load becomes an obvious choice for improvement of dynamics of power system.
Furthermore, the wind and diesel sources are major contributor of power generations in load disturbances and considered as ultimate participating sources to meet the peak load for improvement of dynamics of power system.

**Subjects:** Power & Energy; Systems & Control Engineering; Electrical & Electronic Engineering

**Keywords:** automatic generation control; dynamic performance; multi source power system; HVDC link; renewable energy sources; dynamic search space squeezing strategy

### 1. Introduction

A modern power system is complex and sophisticated with multi area and diverse sources of power generation. The control of electric energy with nominal system frequency and tie-line power interchange within their prescribed limits are very much important. The automatic generation control (AGC) plays an important role in power pool by maintaining scheduled system frequency and scheduled tie-line power in normal operation and during small perturbations. The modern power system consists of diverse sources of power generation such as thermal, hydro and renewable energy power plants having many control areas or regions representing coherent group of generators. The area control error as the controlled output of AGC is driven to zero in order to make the frequency and tie line power deviations of control area to zeros (Elgard, 1982; Kundur, 1994). The environmental drive to promote green energy invites new renewable sources of power generation and their corresponding participation factor are more important for the study of AGC.

Over the last decade, many researchers have proposed several strategies for AGC of power systems in order to maintain the system frequency and tie line power flow within their prescribed limits during normal operation and also during small perturbations. To meet the today's stringent quality requirements, accurate-tools based realistic models with faster solution speed; high degree of reliability is required. While considerable progress has been made in the development of intelligent controllers and their applications to large scale power system still remain a challenging area and a common problem. It is found in literature survey that the early work on AGC was initiated by Cohn (1957) but the design of modern optimal controller concept for interconnected power system was first started by Elgerd and Fosha (1970). The recent past control strategies for automatic generation control of power system are reported by Kumar and Kothari (2005) which includes various control aspects for AGC system incorporating with other additional devices. The gain scheduling control method for AGC of interconnected power system was proposed by Lee, Yee, and Teo (1991). This control is different from other control techniques in terms of robustness to wide range of operating conditions and also easy implementation. Finite-frequency $H^\infty$ controller with state-feedback approach provides superior suspension performances of active suspensions equipped in in-wheel motor driven electric ground vehicles within the concerned frequency (Wang, Jing, Yan, Reza Karimi, & Chen, 2015). The accuracy of dynamic state estimation of multi-area power systems has been improved with the application of Kalman filter and a consensus algorithm (Qing, Karimi, Niu, & Wang, 2015).

There is an evolution of intelligent techniques in recent years. Almost all new algorithms report better results than the previous ones in different engineering fields. Some algorithms give a better solution for some particular problems than others do. It is very important for the selection of the right algorithm that suits to a particular problem. The parameters of the model of a single-mass coupled with a spring and/or a damper system are optimized by using interior-point and firefly algorithms (Klausen et al., 2014). The intelligent controllers such as genetic algorithm (GA) based PI and PID controller (Pinkang, Hengjun, & Yuyun, 2002), PSO based controller (Abdel-Magid & Abido, 2003), bacteria foraging algorithm (BFA) based PI controller (Ali & Abd-Elazim, 2011), differential evolution (DE) algorithm based PI controller (Rout, Sahu, & Panda, 2013), optimal output feedback controller for multi-source system (Parmar, Majhi, & Kothari, 2012b), generalized neural network approach (Chaturvedi, Satsangi, & Kalra, 1999), several classical controllers (Saikia, Nanda, & Mishra, 2011), bat algorithm tuned dual mode PI controller (Sathya & Mohamed Thameem Ansari, 2015), flower
pollination algorithm tuned cascade PI-PD controller (Dash, Saikia, & Sinha, 2016), teaching learning 
based optimized PID controller (Barisal, 2015), moth flame optimization algorithm optimized PID 
controller (Barisal & Lal, 2018), variable structure controllers for interconnected power systems 
(Chan & Hsu, 1981), sliding mode controller (Mohanty, 2015) have been applied in AGC problems.

The growth in size and complexity of electric power system due to nonlinear load characteristics 
and variable operating points has necessitated the use of fuzzy based methods to address satisfac-
torily the performances under small perturbations. Fuzzy based Control of electric power steering 
system through both saturated and constrained controls can ensure EPS system stability and com-
fort driving in the presence of nonlinear friction, disturbance of the road and actuator saturation 
(Saifia, Chadli, Karimi, & Labiod, 2015). A self-tuning fuzzy type PID controller (Yeşil, Güzelkaya, & 
Eksin, 2004), a reinforcement learning approach (Ahamed, Rao, & Sastry, 2002), adaptive neuro-
fuzzy interference system (ANFIS) (Khuntia & Panda, 2012), evolutionary fuzzy PI controller (Juang & 
Lu, 2004), PSO based controller with fuzzy application (Ghoshal, 2004), two fuzzy rules for integral 
and proportional gains PI controller (Chang & Fu, 1997), adaptive fuzzy gain scheduling method 
(Cam & Kocaarslan, 2005) and gray wolf optimization algorithm optimized fuzzy PID controller. Lal 
and Barisal (2017) have been implemented in AGC problems. An ant colony optimization (ACO) algo-

It has been observed in literature survey that most of the researchers adopt thermal-thermal or 
thermal hydro systems in AGC studies. Interestingly, very few papers in literature that considers a 
single area (Mohanty, Panda, & Hota, 2014; Parmar, Majhi, & Kothari, 2012a) for multi-area without 
or with HVDC link connecting two areas (Ibraheem, Nizamuddin, & Bhatti, 2014; Mohanty et al., 
2014; Parmar, et al., 2012a) of realistic power system having generation from thermal, hydro and 
gas units. The bulk power transmission through HVDC transmission lines connected with AC lines 
possess many advantages like fast controllability of HVDC lines through converter control, ability 
to reduce transient stability problem of AC lines other economical and technical operation of power 
system. The DE tuned PID controller (Mohanty et al., 2014) has been applied in a two identical area 
AC-DC system with parallel tie lines for frequency stabilization which outperforms than an optimal 
output feedback controller (Parmar et al., 2012a) for similar power system. Ibraheem et al., (2014) 
have considered two equal sources of power system with diverse sources of power generation and 
proved significant improvements in system dynamic performance by considering parallel AC/DC 
links as interconnection between areas rather than using AC tie lines only. Gozde, Taplamacioglu, 
and Kocaarslan (2012) proposed the artificial bee colony based PI and PID controller parameter tuning 
and its superior performance compared to PSO with transient response analysis method.

There has been considerable progress in intelligent algorithm based controller research work at-
ttempting to better control for AGC systems (Aström & Hagglund, 1995). The Improved PSO based 
optimization (IPSO) is a stochastic optimization technique (Barisal, 2013) and it has hardly been ap-
plicated to tune the controller in AGC studies. The authors have proposed an improved PSO algorithm 
for tuning of PID controller for load frequency control of the present scenario of a realistic power 
system with two unequal areas having multiple sources of power generation including wind and 
diesel power plants (Das, Aditya, & Kothari, 1999) and its superior dynamic performances are com-
pared to that of BFA and PSO tuned PID controller for the same power system under study. Moreover, 
the proposed IPSO algorithm is very simple in concept and easy implementation to tune the control-
ler of AGC for the new realistic power system. The main investigations of the present work:

(1) To propose an improved intelligent algorithm as dynamic search space squeezing strategy 
based particle swarm optimization (IPSO) for the load frequency control of the realistic power 
system.
(2) To optimize the PID controller gains by BFA, PSO, IPSO tuned controller and study of its dynamic performances for above power system.

(3) To compare the dynamic performance of IPSO based PID controller to that of BFA, PSO tuned controller for multi-source multi area power system without and with HVDC link between control areas with 1% step load perturbation in area-1.

(4) To analyze the improvements of dynamic performance of IPSO based tuned PID controller for multi-source two unequal areas without and with HVDC link between control areas with 1% step load perturbation (SLP) in area-1, area-2 and in both areas.

2. System investigated

2.1. Multi source multi area realistic power system

The two identical area power system interconnected by parallel AC-DC tie lines (Ibraheem et al., 2014; Mohanty et al., 2014; Parmar et al., 2012a) which comprises more practical combination of generating units such as reheat thermal, hydro and gas units in each area. However, in the present study two unequal areas of power system, one area having thermal, hydro and wind sources of power generation and the other area with thermal, hydro and diesel power plants participating in AGC is simulated by the proposed evolutionary algorithms based tuned PID controllers using MATLAB Simulink. Furthermore, the generators in each area may or may not participate in the LFC task and the participation rates are not same for all participating generators. The summation of participation factors of all participating generators is equal to unity in each control area. The study was conducted on two unequal areas interconnected power system with plants having 57.47% generation from thermal, 28.73% generation from hydro, 13.8% generation from wind and 13.8% generation from diesel power plants. Transfer function model of multi-source multi area with HVDC link with PID controllers is depicted in Figure 1. The nominal parameters of the power system are given in Appendix A and B. In Figure 1, \( R_1, R_2, R_3 \) and \( R_4 \) are regulation parameters of thermal, hydro, wind and diesel units, respectively. \( U_T, U_H, U_W \) and \( U_D \) are control outputs of thermal, hydro, wind and diesel units, respectively. \( T_{sg} \) is speed governor time constant of thermal unit in sec, \( T_r \) is the steam turbine time constant in sec, \( K_r \) is the steam turbine reheat constant, \( T_{rg} \) is the steam turbine reheat time constant in sec, \( T_{rs} \) is nominal starting time of water in penstock in sec, \( T_{rh} \) is the hydro turbine speed governor reset time in sec, \( T_{rg} \) is the hydro turbine speed governor transient droop time constant in sec, \( B_1, B_2 \) are bias constant of two areas, \( K_{psi} \) and \( T_{psi} \) are the gain and time constant of power system of two areas (\( i = 1, 2 \)), \( K_{dci} \) and \( T_{dci} \) are the gain and time constant of HVDC system of two areas (\( i = 1, 2 \)), \( \Delta F \) is the incremental change in frequency and \( \Delta P \) is incremental load change.

2.2. Control strategy with objective function

The Proportional Integral Derivative controller (PID) is the widespread and popular feedback controller used in many modern industries. The popularity of PID controllers stems in part to their wide applicability to a variety of single input single output applications. PID controller is often used when stability and fast response are required. It is reported in reference (Mohanty et al., 2014) that the DE tuned PID controller outperforms than the DE tuned PI and I controllers for multi-source multi area realistic power system. Keeping in view above, The PID controller is employed in the present paper for comparative performance analysis of a realistic power system.

There are four kinds of performance criteria such as integral of absolute error (IAE), integral of squared error (ISE), integral of time weighted squared error (ITSE) and integral of time multiplied absolute error (ITAE). However, ITAE and ISE criterions are mostly used in AGC studies for their better performance as compared to ITSE and IAE criterion. Systems with ITAE objective functions settle
more quickly than ISE method. Therefore, ITAE is a better objective function among all and considered in present paper.

The objective function for multi source power system may be defined as

\[ J = ITAE = \int_0^{t_{\text{sim}}} \left( |\Delta F_1| + |\Delta F_2| + |\Delta P_{\text{Tie}}| \right) \cdot t \cdot dt \]  

(1)

where \( \Delta F_1 \) and \( \Delta F_2 \) are the frequency deviations of area-1 and area-2, respectively. \( \Delta P_{\text{Tie}} \) is the incremental change in tie line power and \( t_{\text{sim}} \) is the time range of simulation. Minimize \( J \) subject to PID controller gains such as

\[ K_{ij} \min \leq K_i \leq K_{ij} \max, \text{ where, } i = P, I, D \text{ and } j = 1, 2, 3, 4. \]  

(2)

The differential equation of PID controller of each unit of power system that are thermal, hydro, wind and diesel with respective control inputs as \( U_T, U_H, U_W \) and \( U_D \) may be written as

\[ U_T = K_{p1}ACE_j + K_{i1} \int ACE_j + K_{d1} \frac{dACE_j}{dt} \]  

(3)

\[ U_H = K_{p2}ACE_j + K_{i2} \int ACE_j + K_{d2} \frac{dACE_j}{dt} \]  

(4)

where \( j = 1, 2 \), for control areas.

\[ U_W = K_{p3}ACE_1 + K_{i3} \int ACE_1 + K_{d3} \frac{dACE_1}{dt} \]  

(5)

\[ U_D = K_{p4}ACE_2 + K_{i4} \int ACE_2 + K_{d4} \frac{dACE_2}{dt} \]  

(6)
The ACE signal is the area control error which includes the data about the frequency error and the tie line power error for the related control area. They may be represented in (7) and (8) for area-1 and area-2, respectively.

\[
ACE_1 = B_1 \Delta F_1 + \Delta P_{\text{Tie}}
\]

(7)

\[
ACE_2 = B_2 \Delta F_2 + \Delta P_{\text{Tie}}
\]

(8)

The controllers’ gains are tuned by the three evolutionary algorithms according to the ITAE objective function. The intelligent algorithm based optimization are applied increasingly due to their simpler implementing, better performance of converging and less execution time at present (Aström & Hagglund, 1995). The controller parameters can be adjusted very quickly in response to the changes in the plant dynamics. The details of evolutionary algorithms and proposed IPSO algorithm are described in following section.

3. Evolutionary algorithms

The intelligent evolutionary algorithms are well suited to solve complex computational engineering problems. These algorithms are population based stochastic parallel search algorithms differ from traditional optimization techniques by many aspects that are population of solutions, not a single point solution, no limitation of size of the problem, independent of initial guess of the variables, simple and easy to implement, very close to hundred percent success rate, significantly fast and robust due to competition, selection and inherent randomness involved in the process and also incredibly well in solving the realistic AGC problems. For more details of these evolutionary algorithms like BFA (Ali & Abd-Elazim, 2011), PSO and IPSO algorithms are described in reference (Barisal, 2013).

There are several approaches that can be used to improve PSO in general. The size of the population is one of the important factors. Higher population size can increase the chance of faster and precise convergence. The other approach is to achieve a balance between exploration and exploitation. Evolutionary operators such as selection, crossover, and mutation have been used in PSO to keep the best particles, to increase the diversity of the population, and avoid entrapment in a local minimum. The use of mutation operators was explored to mutate parameters like inertia weight. This, according to the authors, helps maintain the diversity in the swarm and helps to escape local optima. The Improved PSO has good balance between exploration and exploitation and plays an important role in avoiding premature convergence during the optimization process.

In PSO the position mechanism of the particle in the search space is updated by adding the velocity vector to its position vector to get an updated position. Over the course of iterations the positions of particles (solutions) are updated by the guidance of the position and velocity vectors and converged to an optimal solution. In an Improved PSO, a constraint treatment mechanism called dynamic search space squeezing strategy is equipped to accelerate the optimization process and simultaneously the dynamic process inherent in the conventional PSO algorithm is preserved. Transmission of knowledge from best particles to other particle during every iteration and there is a refinement of solution over the course of iterations. The technique of parallel search (Population) algorithm evaluates cost function and resulting in a much faster convergence.

When the constant performance (no improvement) of solution is achieved, the dynamic search-space squeezing strategy is activated to accelerate the convergence speed. In this case, the search space is dynamically readjusted (i.e. squeezed) based on the relative distance between gbest and lower and upper limits of \(i\)th controller gains denoted by \(\Delta_{L_i}\) and \(\Delta_{H_i}\) respectively. Both the relative distances are variables, not always equal and constant, which are represented as follows:

\[
\Delta_L^k = \frac{g_{\text{best}}^k - K_{i,\text{min}}}{K_{i,\text{max}} - K_{i,\text{min}}} \Delta_{H_i} = \frac{K_{i,\text{max}} - g_{\text{best}}^k}{K_{i,\text{max}} - K_{i,\text{min}}},
\]

(9)
At iteration $k + 1$, the adjusted limits of gains of controller $i$ are determined to satisfy inequality constraints as follows:

\[
\Delta_{Li}^k + \Delta_{Hi}^k = 1, \quad i = 1, 2, 3, 4. \tag{10}
\]

The limits of gains of controller are changing in iterations but always guided by the location of gbest in the search space. The updated maximum and minimum values are described in (11) and (12), and always satisfied by (2). The convergence curve of Improved PSO and conventional PSO is shown in Figure 2. It is seen that IPSO convergence characteristic is better than PSO. In multi objective and multi constraint problems, it is difficult to find the best compromising solution. A composite ranking index can help the decision-maker in ranking the large number of Pareto optimal solutions.

### 3.1. Parameters tuning of evolutionary algorithms

Optimal parameter combinations for different algorithms are experimentally determined by conducting a series of experiments with different parameter settings before conducting actual runs to collect the results. The optimal parameter setting of bacteria foraging algorithm are given below:

- Number of bacteria = 10
- Number of chemotaxis steps = 6
- Length of swim = 4
- Number of elimination and dispersal events = 4
- Number of reproduction steps = 4
- Probability of elimination and reproduction = 0.25

In PSO, there are three parameters namely inertia constant $w$, velocity $v_{\text{max}}$, and acceleration constants $c_1$, $c_2$ to be adjusted for optimum performance beside swarm size. The different values of PSO parameters such as inertia weight $w$, number of particles $n$, maximum allowable velocity $v_{\text{max}}$, the following selected key parameters as $w_{\text{max}} = 0.5$, $w_{\text{min}} = 0.1$, $v_{\text{max}} = \frac{p_{\text{max}} - p_{\text{min}}}{10}$, $v_{\min} = -v_{\text{max}}$, $c_1 = 1.2$, $c_2 = 1.5$, $n = 20$ give the better performance compared to all other settings in terms best and mean values.

When dynamic search squeezing strategy is activated in case of IPSO, then, the new selected parameters are $w_{\text{max}} = 0.01$, $w_{\text{min}} = 0.0$, $v_{\text{max}} = \frac{p_{\text{max}} + p_{\text{min}}}{20}$, $v_{\min} = -v_{\text{max}}$, $c_1 = 1.2$, $c_2 = 1.5$, $n = 20$.

Figure 2. Convergence characteristics of Evolutionary algorithms.
4. Simulation results

The present work has been implemented in Matlab-7.10.0.499 (R2010a) environment on a 3.06 GHz, Pentium-IV; with 1 GB RAM PC for the controller parameter tuning in automatic generation control. The model of the system under study has been developed in MATLAB/SIMULINK environment and evolutionary algorithms such as BFA, PSO and IPSO algorithm based programs have been written (in .m file). The developed model is simulated in a separate .m file using initial gain scheduling parameters considering a 1% step load perturbation in area-1 at time, \( t = 0 \) s. The objective function is calculated in .m file and used in optimization algorithms for tuning the gains of PID controller for power system under study.

This power system comprises two unequal control areas, one having thermal, hydro and wind and the other with thermal, hydro and diesel power plants, each area having three PID controllers designed for investigation of load frequency control. A step load change of 1% in area-1 is considered at \( t = 0 \) s. The optimal PID controllers’ parameters obtained by different algorithms for the power system with AC lines only and also with AC/DC parallel tie lines are reported in Table 1.

4.1. Analysis of results

The performance index \( J \) or the standard objective function can be defined by Integral of time multiplied absolute error (ITAE) of the frequency deviations of both areas and tie line power of two control areas. It is found that the performance index value is reduced in case of parallel AC/DC links are used between areas than that obtained with only AC tie lines between areas. Therefore, the

| Method          | BFA-controller | Cost index |
|-----------------|----------------|------------|
| Controller parameter | Thermal | Hydro | Wind | Diesel |  
| System with AC lines only | \( K_p = 0.5518 \) | \( K_p = 0.7718 \) | \( K_p = 1.1045 \) | \( K_p = 0.0966 \) | 0.2624 |
|                  | \( K_i = 0.8138 \) | \( K_i = 0.1679 \) | \( K_i = 0.7950 \) | \( K_i = 1.0210 \) |           |
|                  | \( K_d = 0.6316 \) | \( K_d = 0.8660 \) | \( K_d = 1.1429 \) | \( K_d = 0.0999 \) |           |
| System with AC-DC parallel lines | \( K_p = 0.0572 \) | \( K_p = 0.1229 \) | \( K_p = 1.0582 \) | \( K_p = 0.9853 \) | 0.1987 |
|                  | \( K_i = 0.2636 \) | \( K_i = 0.3897 \) | \( K_i = 0.3602 \) | \( K_i = 0.0689 \) |           |
|                  | \( K_d = 0.1110 \) | \( K_d = 1.2052 \) | \( K_d = 0.2493 \) | \( K_d = 0.4148 \) |           |

| Method          | PSO-Controller | Cost index |
|-----------------|----------------|------------|
| Controller parameter | Thermal | Hydro | Wind | Diesel |  
| System with AC lines only | \( K_p = 1.8551 \) | \( K_p = 1.6291 \) | \( K_p = 1.3932 \) | \( K_p = 1.3569 \) | 0.2309 |
|                  | \( K_i = 0.5754 \) | \( K_i = 1.0504 \) | \( K_i = 1.7490 \) | \( K_i = 0.0576 \) |           |
|                  | \( K_d = 1.8814 \) | \( K_d = 1.6392 \) | \( K_d = 1.1354 \) | \( K_d = 1.5188 \) |           |
| System with AC-DC parallel lines | \( K_p = 1.5346 \) | \( K_p = 1.6692 \) | \( K_p = 1.5265 \) | \( K_p = 0.2691 \) | 0.1839 |
|                  | \( K_i = 1.3945 \) | \( K_i = 1.9296 \) | \( K_i = 1.7094 \) | \( K_i = 1.1804 \) |           |
|                  | \( K_d = 1.5045 \) | \( K_d = 0.4696 \) | \( K_d = 0.1632 \) | \( K_d = 0.1182 \) |           |

| Method          | IPSO-Controller | Cost index |
|-----------------|----------------|------------|
| Controller parameter | Thermal | Hydro | Wind | Diesel |  
| System with AC lines only | \( K_p = 1.7372 \) | \( K_p = 1.5677 \) | \( K_p = 1.3674 \) | \( K_p = 0.9698 \) | 0.2036 |
|                  | \( K_i = 0.0334 \) | \( K_i = 0.3874 \) | \( K_i = 1.7768 \) | \( K_i = 1.6664 \) |           |
|                  | \( K_d = 1.6378 \) | \( K_d = 1.8257 \) | \( K_d = 1.4257 \) | \( K_d = 0.1815 \) |           |
| System with AC-DC parallel lines | \( K_p = 1.9759 \) | \( K_p = 0.7936 \) | \( K_p = 0.8048 \) | \( K_p = 1.2413 \) | 0.1464 |
|                  | \( K_i = 0.3409 \) | \( K_i = 0.1480 \) | \( K_i = 1.9657 \) | \( K_i = 0.3087 \) |           |
|                  | \( K_d = 0.5156 \) | \( K_d = 1.3682 \) | \( K_d = 0.8044 \) | \( K_d = 0.7627 \) |           |
| System with AC-DC with nonlinearity | \( K_p = 1.9479 \) | \( K_p = 1.6001 \) | \( K_p = 1.6033 \) | \( K_p = 1.2165 \) | 0.2145 |
|                  | \( K_i = 0.4758 \) | \( K_i = 0.0896 \) | \( K_i = 1.9212 \) | \( K_i = 1.9781 \) |           |
|                  | \( K_d = 0.2172 \) | \( K_d = 1.9199 \) | \( K_d = 1.5315 \) | \( K_d = 0.2813 \) |           |
incorporation of DC link in parallel with AC link improves the dynamic stability of the power system and also reduces the cost index. The transient performances of the power system with AC tie lines only and also with AC/DC parallel tie lines by the application of three heuristic algorithms are shown.

Figure 3. Transient performances of multi source power system with AC link using PID controller for Evolutionary algorithms for 1% step load change in area-1. (a) $\Delta F_1$ vs. time, (b) $\Delta F_2$ vs. time and (c) $\Delta P_{tie}$ vs. time.
in Figures 3 and 4, respectively. It has been observed that the IPSO method based PID controller in comparison to BFA and PSO method is indeed more efficient in improving the damping characteristics of power system and frequencies and tie line power oscillations are effectively suppressed by the proposed controller as shown in Figures 3 and 4. It is found that peak deviations in frequency with negligible oscillations are lower in case of proposed IPSO tuned PID controller to that of BFA tuned and PSO tuned PID controllers for the same system with AC lines as shown in Figures 3(a) and (b). The tie line power deviations has been seen lower in case of IPSO tuned PID controller to that of BFA.
tuned and PSO tuned PID controllers for the same system with AC lines as shown in Figure 3(c). Similarly, the frequency deviations of area-1 and area-2 and also tie line power deviation for the same system with AC/DC parallel lines are depicted in Figure 4(a)-(c), respectively. Moreover, the proposed IPSO tuned PID controller outperforms to that of BFA and PSO controllers in all cases. The pattern of eigen values of power system under investigation are provided in Table 2. It is clear from the Table 2 that none of the eigen values is in the right half of "s" plane, therefore the system is stable for both power system models with AC tie lines as well as AC/DC parallel lines. Some eigen values have higher negative real parts in case of AC/DC parallel lines and these increments in eigen values improve the stability of power system. Further more, the reduced values of imaginary parts of eigen values may result quick and smooth decay of system response. The dynamic responses of power system models for 1% step load perturbation in area-1, area-2 and both areas are shown in Figures 5–7, respectively. The investigations after thorough looking to the dynamic response plots reveal that in case of load disturbance in either of two interconnected control areas, the system states belong to area of disturbance experience more deviations as compared to other control area. Hence, it can be noted that the effect of disturbance has local dominance but affects the dynamics of other control area also due to the presence of weak tie between control areas. When the load disturbance occurs in both areas simultaneously as shown in Figure 7, then the dynamics of both

| Table 2. Eigen values of power system under investigation |
|---------------------------------------------------------|
| Eigen values of power system with AC lines              |
| -24.4229                                                |
| -19.7230 + 4.3845i                                      |
| -19.7230 - 4.3845i                                      |
| -12.8949                                                |
| -9.9980                                                 |
| -5.5464                                                 |
| -4.3398 + 1.8360i                                       |
| -4.3398 - 1.8360i                                       |
| -0.0444 + 2.3271i                                       |
| -0.0444 - 2.3271i                                       |
| -2.8666                                                 |
| -2.4097                                                 |
| -1.5149                                                 |
| -1.0412 + 0.0920i                                       |
| -1.0412 - 0.0920i                                       |
| -0.5614 + 0.3343i                                       |
| -0.5614 - 0.3343i                                       |
| -0.7307                                                 |
| -0.0796                                                 |
| -0.0983                                                 |
| -0.0425                                                 |
| -0.0348                                                 |
| -0.0000 + 0.0000i                                       |
| -0.0000 - 0.0000i                                       |
| -0.0000                                                 |
| -0.0000                                                 |
| 0.0000 + 0.0000i                                        |
| 0.0000 - 0.0000i                                        |
| 0.0000                                                  |

Eigen values of power system with AC/DC lines
-24.4233
-19.7230 + 7.9337i
-19.7230 - 7.9337i
-17.0040 + 7.9337i
-17.0040 - 7.9337i
-12.8279
-11.0356 + 3.7035i
-11.0356 - 3.7035i
-1.8401 + 5.2007i
-1.8401 - 5.2007i
-3.6716
-3.5425
-1.9912
-1.9285
-1.0809 + 0.1816i
-1.0809 - 0.1816i
-0.3653 + 0.3117i
-0.3653 - 0.3117i
-0.5807
-0.1769
-0.1068
-0.0968
-0.0363
-0.0347
0.0000
-5.0000
-5.0000
0.0000 + 0.0000i
0.0000 - 0.0000i
-0.0000
areas are affected due to increase in generation from each participating sources in each area to meet its own load demand.

It has been found that the peak deviations with frequency with negligible oscillations are lower in case of power system with AC/DC tie line link in comparison to power system with AC tie line only as shown in Figure 5(a) and (b). Furthermore, the deviation in tie line power has been observed to be lower for power system with AC/DC parallel lines in comparison to power system only AC tie lines as shown in Figure 5(c). The frequency and tie line power deviation vanishes under steady state conditions as the generation in the area from different sources increases to meet the load demand. It is found that the increase in generation from wind sources is more and fast as compared to thermal and hydro sources for meeting the load demand as shown in Figure 5(d). Furthermore, the hydro generation is less and sluggish during load disturbance in comparison to thermal source power contribution towards meeting the load demand. Under steady state conditions the area-1 will meet the
increase in its own load demand, therefore the deviations in power generation vanishes in area-2 as shown in Figure 5(e).

Similar results for the dynamic response of the power system has been obtained for 1% step load increase in area-2 as shown in Figure 6. The frequency and tie line power deviations are lesser in case of AC/DC parallel lines in comparison to AC tie lines only as shown in Figure 6(a)–(c). Under steady state conditions the area-2 will meet the increase in its own load demand, therefore the deviations in power generation vanishes in area-1 as shown in Figure 6(d). It is found that the increase in generation from diesel sources is more and fast as compared to thermal and hydro sources for meeting the load demand as shown in Figure 6(e). When 1% step load perturbations applied in both areas, the dynamic performance in terms of frequencies and tie line power deviations are better in power
system with AC/DC parallel lines between control areas as shown in Figure 7(a)–(c). Under steady state conditions both areas will meet the increase in its own load demand, therefore the deviations in power generation from all sources in each area has been observed in Figure 7(d) and (e). It is found that increase in generation from wind and diesel sources are more and fast in comparison to thermal and hydro sources during step load perturbations in power system. Therefore, these diverse sources like wind and diesel can be considered as ultimate sources in AGC studies for improvement of dynamics of system to meet the peak load demand.

Figure 7. Transient performances of multi source power system using IPSO algorithm for 1% step load perturbation in both areas. (a) \( \Delta F_1 \) vs. time, (b) \( \Delta F_2 \) vs. time, (c) \( \Delta P_{\text{Tie}} \) vs. time, (d) \( \Delta P_{G1} \) vs. time and (e) \( \Delta P_{G2} \) vs. time.
4.2. Analysis with addition of non-linearity

4.2.1. Governor dead band

A dead band is considered as a neutral zone or dead zone and an interval of a signal domain or band where no action occurs. The system is “dead”—i.e. the output is zero. Dead band regions can be used
in voltage regulators and other controllers to prevent oscillation or repeated activation-deactivation cycles. A form of dead band that occurs in mechanical systems, compound machines such as gear trains is backlash. It has been found that the backlash nonlinearity tends to produce a continuous sinusoidal oscillation with a natural period of about 2 s. An approximate value of dead band has been considered in present work as backlash of 0.05%.

4.2.2. Generation rate constraint
There is a maximum limit to the rate of change in generation power of a steam plant in real situation. It has been shown in (Chan & Hsu, 1981) that the dynamic responses of the system with the presence of Generation rate constraint (GRC) have larger overshoots and longer settling times, compared to the system without considering GRC. Furthermore, if the parameters of the controller are not chosen properly, the system may become unstable. A generation rate limitation of 0.1 p.u. per minute is considered here, i.e. $\Delta P_g \leq 0.01 \text{ p.u./minute} = 0.0017 \text{ p.u./sec}$. 

![Figure 9. Transient performances of multi source power system using IPSO algorithm for 1% step load perturbation in one area with parameter variation (a) $\Delta F_1$ vs. time with variation in $B$, (b) $\Delta F_1$ vs. time with variation in $R$ and (c) $\Delta F_1$ vs. time with variation in $T_{12}$](image-url)
When nonlinearity are added in power system with dc link, the controller parameters once again tuned to give the better results with controller in terms of dynamic performance. When 1% step load perturbations applied in both areas, the dynamic performance in terms of frequencies and tie line power deviations are better in power system without nonlinearity between control areas as shown in Figure 8(a)–(c).

4.3. Sensitivity analysis

To check the strength of IPSO optimized PID controller obtained at nominal condition, the bias coefficient ($B$), speed governor regulation ($R$) and synchronizing coefficient ($T_{12}$) are varied in the range of ±25% from its nominal values and performance of the system is studied. The transient performance of the system with parameter variation is shown in Figure 9(a)–(c). As seen from Figure 9, the system responses are almost remaining same as nominal condition. Further, the system is subjected to random load perturbation as given in Figure 10(a). The response of the system for area1 is given in Figure 10(b). Figure 10(b) reveals that satisfactory system response is obtained with proposed approach following random load perturbation. So, it can be concluded that the proposed controller is a robust controller.

5. Conclusion

In this paper, three evolutionary algorithms named BFA, PSO and IPSO are proposed to tune the parameters of PID controller to improve the dynamic response of multi-source two unequal area non linear power systems. A more realistic power system with diverse sources such as thermal and hydro in both areas, wind in area-1 and diesel in area-2 and interconnected by parallel AC/DC lines has been considered to demonstrate the proposed methods. An integral time absolute error of the frequency deviation of both areas and tie line power is taken as the objective function to improve the system response. Simulation results emphasis that the proposed IPSO tuned PID controller is robust in its operation and gives a superb damping performance for frequency and tie line power deviation following a step load perturbation (SLP) compared to BFA tuned controller and PSO tuned PID controller for similar system. To strengthen the robustness, sensitivity analysis is performed by varying...
B, R and T ± 25% from its nominal values; then the system is subjected to random load perturba-
tion and satisfactory system response is observed. Furthermore, the use of DC link in parallel with AC
link as an area interconnection not only improves the dynamic stability of the system but also lowers
the cost index. It is revealed that in case of load disturbance in either of two interconnected control
areas, the system states of disturbed area experience more deviations as compared to other control
area. So, it can be concluded that the effect of disturbance has local dominance but transfers to
other area due to the weak tie between the control areas. Further increase in generation from wind
and diesel sources are more and fast in comparison to thermal and hydro sources during step load
perturbations in both areas of power system. Therefore, diverse sources like wind and diesel are
major contributor in load disturbances and considered as ultimate participating sources to meet the
peak load in AGC studies for further improvement of dynamics of power system. The fuzzy based
adaptive model predictive control theme for solving of AGC problems may be attempted in future
work in order to enhance system dynamic performance.

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Author details
A.K. Barisal1
E-mail: a_barisal@rediffmail.com
Somanath Mishra2
E-mail: somom82@gmail.com
1 Department of Electrical Engineering, Veer Surendra Sai
University of Technology, Burla, Odisha, India.
2 Department of Electrical Engineering, Mahanija Institute of
Technology, Bhubaneswar, Odisha, India.

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Appendices: System data

Appendix A

Power system [A new hybrid system]

Thermal and hydro data is from Ibraheem, Nizamuddin and Bhatti, and wind diesel data from T. S. (2014) and Das et al. (1999)

The typical values of system under study are given below:

\[ f = 60 \text{ Hz}; \quad B_1 = B_2 = 0.439 \text{ pu MW/Hz}; \quad P_r = 2000 \text{ MW (rating)}; \quad P_l = 1840 \text{ MW (nominal loading)}; \]
\[ R_1 = R_2 = R_3 = R_4 = 2.4 \text{ Hz/pu MW}; \quad T_{sg} = 0.08 \text{ s}; \quad T_i = 10.2 \text{ s}; \quad K_i = 0.3; \quad T_i = 0.3 \text{ s}; \quad K_i = 0.5747; \quad K_{1u} = 0.2873; \]
\[ K_w = 0.138; \quad K_D = 0.138; \quad T_{gh} = 0.2 \text{ s}; \quad T_{rh} = 28.75 \text{ s}; \quad T_{th} = 5 \text{ s}; \quad T_{w1} = 1.1 \text{ s}; \quad K_{w2} = 1.25; \quad K_{w3} = 1.3; \quad T_{w1} = 0.6 \text{ s}; \]
\[ T_{w2} = 0.041 \text{ s}; \quad K_0 = 16.5; \quad T_{02} = 0.025 \text{ s}; \quad T_{ps} = 20 \text{ s}; \quad a_{12} = -1; \quad K_{ps} = 120 \text{ Hz/pu MW}; \quad T_{dc} = 0.2 \text{ s}; \quad K_{dc} = 1; \]
\[ T_{12} = 0.0545 \text{ pu}. \]

Appendix B

Non-linearity

The considered final values of GRC and Dead band are given below.

GRC Hydro Upper limit = 0.045 p.u/sec
GRC Hydro Lower limit = −0.06 p.u/sec
GRC Thermal Upper limit = 0.0017 p.u/sec
GRC Thermal Lower limit = −0.0017 p.u/sec
Dead-band of Thermal = 0.0005
Dead-band of Hydro = 0.0002