IMO-based novel adaptive dual-mode controller design for AGC investigation in different types of systems

Gayatri Mohapatra, Manoj Kumar Debnath and Krushna Keshab Mohapatra

Abstract: This article deals with a novel adaptive controller known as dual-mode proportional-integral-derivative (DMPID) controller employed to regulate the frequency of a three-area thermal-type interconnected system including nonlinearity in the form of generation rate constraints. The DMPID controller is tuned by ions motion optimization (IMO) technique to acquire its suitable gains by employing integral absolute error. The dynamic characteristics of the multi-area network with the above-mentioned control methodology are compared with the IMO-tuned PID controller and a previously published method such as bacteria foraging optimized integral controller to establish its supremacy. Further, case studies confirm the robustness of the proposed control approach while subjected to various system loadings, different positions of SLP and parameter variations. Also, the robustness of the recommended controller is validated in the presence of time delays. Finally, the proposed controller is applied in another multi-source model to prove its adaptability.

1. Introduction

The extension of the power system as well as the enhancement of its power capacity increase the chances of abnormal functioning of the system. The abnormal functioning includes considerable deviations in frequency and tie-line power under sudden and abnormal load variations.
disruptions in the normal performance of the power system can be taken as an involvement of misalliance between the generations and loads (Kundur, 1994). In large-scale power systems, automatic generation control (AGC) (also known as load frequency control (LFC)) has a major role to play for the stability of the system. The main function of the AGC in a large-scale power system is to regulate the change of frequency and the interline power within acceptable condition (Concordia & Kirchmayer, 1953).

A substantial amount of research exploration has been done in this domain and it has been observed that LFC has a pivotal part to play in large-scale power systems. The literature review reveals that in the past eras, many researchers suggested various control methods to control the power flow of interconnected network. The whole study basically focuses on the designing of an optimal controller. Fuzzy-based integral controllers have been proposed with the genetic algorithm (GA) optimization technique to control the active power of thermal generating systems associated with reheat and non-reheat model in the article by Ghoshal and Goswami (2003). A notable artificial neural network technique (Zeynelgil, Demiroren, & Sengor, 2002) has been suggested for the multi-area power system to control active power generation. In the article by Ghoshal (2004), proportional-integral-derivative (PID) controller is tuned by particle swarm optimization (PSO) process to regulate the system generation automatically. To accelerate the control action and to overcome the pitfalls of conventional controllers, fuzzy logic-based controllers were projected in the interconnected system to control the frequency (Çam & Kocaarslan, 2005). A hydro-thermal-based system is considered in a paper by Khuntia and Panda (2010) to study the execution of AGC with several kinds of controllers. Proportional plus integral controller (Gozde & CengizTaplamacioglu, 2011) tuned by craziness-based PSO was suggested for the frequency regulation in interconnected thermal power system. AGC can also be analyzed under the deregulated environment (Debbarma, Saikia, & Sinha, 2013) by using a non-integer controller for a hybrid power system. Dey, Ghosh, Ray, & Rakshit, (2012) presented H∞ control-based frequency regulation introducing communication time delay. Intelligent adaptive neuro-fuzzy inference system control approach has been developed to study the simulation of frequency and tie-line power of interconnected power system (Khuntia & Panda, 2012). Over the past decades, many methodologies like bacteria foraging tuned controllers (Nanda, Mishra, & Saikia, 2009), ant colony optimized PID controller (Omar et al., 2013) and firefly optimized fractional order controller (Debbarma, Saikia, & Sinha, 2014) have been suggested for unified power system to have control on system frequency. Multi-objective non-dominated sorting GA-II has been introduced in the article by Wu, Tsakalis, Heydt, Panda, and Narendra (2013) for the hybrid type power system to have control in deviation of power system constraints. A cascaded controller having the combination of both PI- and PD-type controller along with fuzzy logic principle was suggested in the paper by Mudi and Pal (1999) for LFC. Differential evolution algorithm was designed and scrutinized to find out the optimized gains of the PI controller (Rout, Sahu, & Panda, 2013). The performance of a hybrid power system with a PID controller (Mohanty, Panda, & Hota, 2014) was examined for frequency regulation. In an article by Barisol (2015), the gains of PID controller were tuned by teaching-learning-based optimization method to achieve better system responses in terms of frequency and tie-line power. Further, another newly introduced chaotic optimized PID controller (Farahani, Ganjefar, & Alizadeh, 2012) was suggested for a multi-area power system for frequency regulation. Reinforced learning-based neural network controller (Saikia et al., 2011) was introduced on a hydro-thermal-based hybrid system to reduce the frequency error during disturbances. The effects of time delay in the power system were discussed in the article by Wu, Tsakalis, and Heydt (2004). A newly invented model predictive control was suggested in a wind farm for the regulation of frequency (Liu, Zhang, & Lee, 2017). The act of AGC was enhanced by using a tuned fractional order fuzzy PID (FO-FPID) controller along with redox flow batteries in a hydrothermal gas power system (Arya, 2017). An integrated adaptive learning approach along with improved sliding mode control technology (Mu, Tang, & Haibo, 2017) was offered to control the frequency in the interconnected system. In 2017, linear matrix inequality technique was employed for AGC analysis in a unified power system having communication delays (Ojaghi & Rahmani, 2017). System nonlinearity was considered in the article by Jagatheesan et al. (2017) for LFC.
investigation using flower pollination algorithm. LFC issues were also effectively resolved in a deregulated power system (Pappachen & Peer Fathima, 2017) and smart grid power system (Singh, Kishor, & Samuel, 2017). A novel optimization approach by hybridizing differential evolution and grey wolf optimization algorithm was developed and implemented with optimal fuzzy logic-based PID Controller for LFC analysis (Debnath, Mallick, & Sahu, 2017). Debnath, Jena, & Ranjan (2017) introduced a novel cascaded controller based on the principle of fuzzy logics for AGC inspection in different types of the interconnected system. In Arya (2018), filter plus double integral controller was added with a fuzzy PID controller to form a novel control strategy in the field of AGC. An efficient hybrid type PID-Fuzzy-PID controller was developed by Debnath, Jena, and Sanyal (2019) for frequency regulation in the unified power system. Arya (2019) employed a fractional calculus-based Fuzzy-PID controller for LFC investigation in a multi-area hydro-thermal system integrating storage units.

2. Novelty
The literature survey reflects these optimization techniques and controller design play an important role in AGC. Behzad Javidy, Abdolreza Hatamlou and Seyedali Mirjalili proposed an optimization technique known as ions motion optimization (IMO) algorithm (Javidy, Hatamlou, & Mirjalili, 2015), which serves well for parameter optimization of the controller in AGC. A detailed investigation implies that PID controller is used in most of the cases due to its simplicity but PID controllers do not able to perform well in the combined mode in many control processes. To extract the best of integral/derivative/proportional controller, a dual-mode PID controller tuned with IMO is considered in this article to address the various AGC issues. The salient points of the research work in this article are

(i) Design of a novel control strategy based on dual-mode PID (DMPID) controller for AGC in a three-area thermal power system in Matlab Simulink environment.
(ii) Optimization of scaling factors of the projected DMPID controller employing IMO technique.
(iii) Evaluation and comparison of the performance of the designed control approach in the field of AGC so as to prove its supremacy over other methods.
(iv) Validation of system performance in the presence of communication time delay.
(v) Extension of analysis in a multi-source power system to verify the adaptability of the proposed control scheme in the field of AGC.

3. System investigated
In this proposed work, three unequal thermal systems have been considered. The ratings of the three thermal areas are 2000, 4000 and 8000 MW, respectively. Each thermal system is equipped with a single reheat turbine with a generation rate constraint (GRC) of 3% per minute. The limited movements of thermal and mechanical segments are considered as a restriction for improving generator output power. Ignoring these constraints may result in wear and tear of the control mechanism and hence GRC is considered in the designed system. Further, the addition of communication time delay amplifies system nonlinearities. Here, a communication time delay is introduced between each generating unit and the center of the controller. The time delay may vary from 100 to 250 ms (Wu et al., 2004). In some cases, it may be of the order of some seconds (Mu et al., 2017). The minimal values of dissimilar parameters of the deliberated systems have been referred from Nanda et al. (2009) and these are listed in appendix A. Figure 1 signifies the simulation model of the designed system with novel dual-mode PID controller. The dynamic responses of the system in terms of frequency and tie-line power deviations are scrutinized using MATLAB (R2016a) software. The optimization of gains of the DMPID controller has been executed by implementing the IMO process considering integral time absolute error (ITAE) as fitness function expressed by Equation (1).
where \( \text{ACE}_i \) is the area control error of the \( i \)th area.

**4. Dual-mode PID controller structural design**

PID controller is still deliberated as the utmost demandable controller for its simple construction and reliable nature. In conventional PID mode, the individual advantage of the proportional, integral and derivative controller cannot be extracted. So here a novel dual-mode PID is proposed where the best of all mode can be derived based on the actuating signal. Further, PID controller also needs the least involvement of human power when compared to other existing controllers. The transient performance of the closed-loop system is improved by increasing the proportional gain of the system, and simultaneously the rise time is also decreased by the help of the proportional controller. The addition of an integral controller to the proportional controller brings the steady-state error to zero, which is never possible with only the proportional controller. But, the battle between the accuracy of static and dynamic characteristics never ends with the help of the proportional and integral (PI) controller. The PI controller yields the least deviation and large settling time as compared to the integral controller. As a result, more oscillations have appeared in the transient response of the PI controller. To overcome the difficulties, a dual-mode controller is injected into the system obtaining the benefits of PI controller independently. In the proposed control strategy, either the proportional or integral controller is chosen at any given point of time which entirely depends upon the magnitude of the error signal obtained. On the other hand, the derivative controller has the adequate ability to enhance the stability of the designed system, moderates overshoot, and also enriches the transient response. So, in addition to the integral/proportional controller, a derivative controller is added to extract suitable control action. The structure of the offered dual-mode PID controller is depicted in Figure 2. Mathematically, the behavior of the suggested DMPID controller can be expressed as follows:

\[
\text{ITAE} = \int_0^\infty t(\text{ACE}_i) \, dt
\]
When $\frac{d(ACE)}{dt} > \varepsilon$, the DMPID controller acts under proportional + derivative mode of operation.

When $\frac{d(ACE)}{dt} \leq \varepsilon$, the DMPID controller acts under integral + derivative mode of operation.

Keeping in view of system dynamics, the value of the $\varepsilon$ is taken as 0.002 (a small value).

5. IMO algorithm

Population-based algorithms can also be categorized based upon the different inspiration methodology such as swarm-inspired (e.g. PSO), evolution-inspired (e.g. differential evolution) and physics-inspired algorithms (e.g. IMO). IMO was developed by Javidy, Hatamlou and Mirjalili in 2015 (Javidy et al., 2015). The main advantages of this algorithm are low complexity, faster convergence and avoidance of local optima. The various steps involved in this algorithm are described as follows.

1. Inspirations

In 1834, the Greek term “ION” was coined by an English physician Michael Faraday which means charged particles. The ions can be divided into two types: (1) the positively charged ion called as “cation” and (2) the negatively charged ion called as “anion”. One of the properties of ions is that ions with similar charge (i.e. ++ or –) will repel each other and ions with dissimilar charge (i.e., +- or -+) will attract each other. This property of ions is the inspiration for the IMO algorithm. Figure 3 depicts the property of ions as well as the inspiration of the IMO algorithm.

The ions characterize the candidate solution and owing to the attraction and the repulsion force, the ions move in the search space. Based upon the fitness, the ions are evaluated and the fitness of the ion is proportional to the objective function of the problem. The anions move to the best cations and vice versa. The size of the force represents the momentum of the ions.

2. Liquid Phase (Diversification)

In the liquid phase, the repulsion forces are ignored for the investigation of search space as the attraction forces between the ions with charges of opposite sign are more. The mathematical
expression for the attraction force, which has only one factor as the distance between them, is given as follows:

\[ AF_{ij} = \frac{1}{1 + e^{-0.1/AD_{ij}}} \]  \hspace{1cm} (2)

\[ CF_{ij} = \frac{1}{1 + e^{-0.1/CD_{ij}}} \]  \hspace{1cm} (3)

where \( AD_{ij} \) is the distance of the \( i \)th anion to the best cation in the \( j \)th dimension, which can be further expressed as

\[ AD_{ij} = |A_{ij} - C_{bestj}| \]  \hspace{1cm} (4)

where \( CD_{ij} \) is the distance of the \( i \)th cation to the best anion in the \( j \)th dimension, which can be further expressed as

\[ CD_{ij} = |D_{ij} - A_{bestj}| \]  \hspace{1cm} (5)

\( j \) and \( i \) denote the dimension and the ion index, respectively.

\( AF_{ij} \) and \( CF_{ij} \) point towards the resultant attraction force of anions and cations, respectively.

Then, the expressions for the positions of the charges are updated as given by the following equations:

\[ A_{ij} = A_{ij} + AF_{ij} \times (C_{bestj} - A_{ij}) \]  \hspace{1cm} (6)

\[ C_{ij} = C_{ij} + CF_{ij} \times (A_{bestj} - C_{ij}) \]  \hspace{1cm} (7)

3. Crystal Phase (Intensification)

In this phase, convergence at the local optimal point occurs. To solve the problem of local optima entrapment, it is needed to follow a phenomenon where a foreign force is applied to get a repulsive strength cracking the solid apart. Mathematically,

if \((C_{bestfit} \geq C_{worstfit}/2 \text{ and } A_{bestfit} \geq A_{worstfit}/2)\)

\[ if \text{ rand()}>0.5 \]

\[ A_i = A_i + \phi_i \times (Cbest - 1) \]

else
\[ A_i = A_i + \phi_1 \times (C_{\text{best}}) \]

end if

if rand()>0.5
\[ C_i = C_i + \phi_2 \times (A_{\text{best}} - 1) \]
else
\[ C_i = C_i + \phi_2 \times (A_{\text{best}}) \]
end if

if rand()<0.05
Re-initialize\( A_i \) and \( C_i \)
end if

end if

Here, \( \phi \) is denoted for random number limiting between \([-1, 1]\).

From the above, \( C_{\text{worst fit}} \) & \( C_{\text{best fit}} \) are denoted for the worst cation's fitness and best cation's fitness, respectively.

Similarly, \( A_{\text{worst fit}} \) & \( A_{\text{best fit}} \) are denoted for the worst fitness of the cations and best fitness of the anions, respectively.

6. Result analysis
In this research article, IMO-tuned DMPID controller is employed for a three-area power system under various circumstances. Three controller parameters in each area that means as a whole nine parameters are being optimized by the help of IMO method simultaneously. For the optimization process, the size of the population and maximum iteration has been considered as 100 each. The following case studies are made to investigate the transient behavior of the designed system.

6.1. Case-1: SLP in area1 only
A disturbance of 1% is injected in area 1. Under this condition, suitable parameters of the projected DMPID controllers are attained with the help of IMO technique and these are grouped in Table 1. Deviations in frequency and fluctuations of interline power have been examined for the stability of the system. The deviations in frequency in area 1 (\( \Delta f_1 \)), area 2 (\( \Delta f_2 \)) and area 3 (\( \Delta f_3 \)) are depicted in Figures 4–6. The deviations of interline power between areas 1 and 3 (\( \Delta P_{\text{tie}1-3} \)) and areas 1 and 2 (\( \Delta P_{\text{tie}1-2} \)) are revealed in Figures 7 and 8. The effectiveness of the designed model is proved by comparing the dynamic responses with the conventional PID controller. The transient response analysis on the basis of maximum overshoot, undershoot and settling time of all deviations are listed in Table 2. In order to show the improvement of the designed method, a comparison of output is made with the published paper (Nanda et al., 2009) of a reputed journal. From the responses (Figures 4–8) and Table 2, it is established that the offered technique provides more stability in the scrutinized system for AGC.

6.2. Case-2: SLP in all areas simultaneously
A disturbance of 0.01 p.u has been applied in all areas of the described system simultaneously. The fluctuations of frequency and deviations of interline power are depicted in Figures 9 and 10, respectively. These figures signify that the described system is stable regardless of the location of step load perturbation (SLP).
| Algorithm       | Control area 1 | Control area 2 | Control area 3 |
|-----------------|----------------|----------------|----------------|
| PID             | $Z_i^p = 0.2649$ | $Z_i^p = 0.2548$ | $Z_i^p = 0.1000$ |
|                 | $Z_i^z = 1.4709$   | $Z_i^z = 1.0000$   | $Z_i^z = 0.8863$   |
| DMPID           | $Z_i^d = 0.2191$   | $Z_i^d = 0.2799$   | $Z_i^d = 0.7682$   |
|                 | $Z_i^d = 0.2191$   | $Z_i^d = 0.2799$   | $Z_i^d = 0.7682$   |

Table 1: Optimal gains of IMO tuned PID and DMPID controllers with application of an SLP of 0.01 p.u. in area 1

BFOI (Nanda et al., 2009)

Mohapatra et al., Cogent Engineering (2020), 7: 1711675
https://doi.org/10.1080/23311916.2020.1711675
Figure 4. Frequency deviation in area 1 with application of an SLP of 0.01 p.u. in area 1.

Figure 5. Frequency deviation in area 2 with application of an SLP of 0.01 p.u. in area 1.

Figure 6. Frequency deviation in area 3 with application of an SLP of 0.01 p.u. in area 1.
In the next analysis, SLP of area 1 is increased from 1% to 5% in a step of 1%. Under this situation, the response specifications (undershoots, settling time and overshoots) of the system are noted and grouped in Table 3. From Table 3, it can be stated that the projected control strategy is robust as the system stability remains intact even though the loading changes widely.

6.3. Case-3: parameter variations

Further, the sensitivity of the simulated model is checked by modifying the system parameters. By varying all the time factors of the system by 10%, the sensitivity is analyzed with the existing controller gains. By applying an SLP of 0.01 p.u. in area 1, the frequency deviations, and the interline power deviations with 10% increase and decrease of all time constants are shown in Figures 11 and 12. These figures indicate that the system is stable even the parameters of the system are changed which verifies the robustness of the controller.
6.4. Case-4: random system loading

Although the system loading is randomly changed, there is no effect on the dynamic stability of the system using the proposed control methodology. Here, the system loading in area 1 is varied by following a random loading pattern as shown in Figure 13. Under such condition, the system constraints (frequency, interline power) are displayed in Figures 14 and 15. The figures reflect the consistency of stability of the system and establish supremacy of the suggested control approach under random loading condition. This analysis again proves the robustness and sensitiveness of the recommended control technique.

6.5. Case-5: communication time delay

For this case, a communication time delay (Wu et al., 2004) in each area is considered which increases the system nonlinearities. With a communication time delay of 50 ms, the dynamic behavior of the closed-loop system is observed with the recommended control approach by applying an SLP of 0.01 p.u. in area 1. The frequency deviations and tie-line power oscillations with 0.05 s time delay are depicted in Figures 16 and 17. These simulation results reflect the reliability of the system and hence prove the robustness of the controller which can compensate the time delay.

6.6. Performance indices

To estimate the responses of the proposed control technique, different performance indices are computed with various error functions when an SLP of 0.01 p.u. is applied in area 1. It is well known that smaller is the value of these performance indices, better is the performance of the system.

| Frequency deviations | Performance evaluative factors | BFOI (Nanda et al., 2009) | PID | Dual-mode PID |
|----------------------|--------------------------------|-------------------------|-----|---------------|
| Δf₁                  | Overshoots (Hz)               | 0.0096                  | 0.0063 | 0.0000       |
|                      | Undershoots (Hz)              | −0.0199                 | −0.0148 | −0.0090     |
|                      | Tₜ in sec (0.05% band)        | 25.6986                  | 8.0403  | 3.6745        |
| Δf₂                  | Overshoots (Hz)               | 0.0050                  | 0.0000  | 0.0000       |
|                      | Undershoots (Hz)              | −0.0096                 | −0.0046 | −0.0026     |
|                      | Tₜ in sec (0.05% band)        | 20.8329                  | 8.4370  | 5.9987        |
| Δf₃                  | Overshoots (Hz)               | 0.0018                  | 0.0000  | 0.0000       |
|                      | Undershoots (Hz)              | −0.0083                 | −0.0036 | −0.0021     |
|                      | Tₜ in sec (0.05% band)        | 11.9358                  | 8.7657  | 6.5810        |
| ΔPᶜᵃˡ-₁-₂            | Overshoots (PU)               | 0.0018                  | 0.0001  | 0.0001       |
|                      | Undershoots (PU)              | −0.0131                 | −0.0073 | −0.0038     |
|                      | Tₜ in sec (0.05% band)        | 21.6156                  | 15.2116 | 10.8073      |
| ΔPᶜᵃˡ-₁-₃            | Overshoots (PU)               | 0.0027                  | 0.0015  | 0.0008       |
|                      | Undershoots (PU)              | −0.0015                 | 0.0000  | 0.0000       |
|                      | Tₜ in sec (0.05% band)        | 11.8672                  | 5.1508  | 3.1068        |
| ΔPᶜᵃˡ-₂-₃            | Overshoots (PU)               | 0.0021                  | 0.0011  | 0.0006       |
|                      | Undershoots (PU)              | −0.0002                 | 0.0000  | 0.0000       |
|                      | Tₜ in sec (0.05% band)        | 5.7982                   | 4.2108  | 3.6745        |
The various performance indices are integral absolute error (IAE), ITAE, integral squared error (ISE) and integral time squared error (ITSE), which are described as follows:

\[
IAE = \sum_{i=1}^{3} \int_{0}^{100} (|\Delta ACE_i|) dt
\]  

(8)

\[
ITAE = \sum_{i=1}^{3} \int_{0}^{100} t(|\Delta ACE_i|) dt
\]  

(9)

\[
ISE = \sum_{i=1}^{3} \int_{0}^{100} (\Delta ACE_i)^2 dt
\]  

(10)

\[
ITSE = \sum_{i=1}^{3} \int_{0}^{100} t(\Delta ACE_i)^2 dt
\]  

(11)
Table 3. Performance evaluative factors of $\Delta f_1$, $\Delta f_2$, and $\Delta f_3$ for different loading conditions in area 1

| $\Delta P_L$ | $\Delta f_1$ | $\Delta f_2$ | $\Delta f_3$ |
|-------------|-------------|-------------|-------------|
|             | $U_{sh}$ in Hz | $S_{sh}$ in Hz | $O_{sh}$ in Hz | $T_{sh}$ in sec | $U_{sh}$ in Hz | $S_{sh}$ in Hz | $O_{sh}$ in Hz | $T_{sh}$ in sec | $U_{sh}$ in Hz | $S_{sh}$ in Hz | $O_{sh}$ in Hz | $T_{sh}$ in sec |
| 1% SLP      | -0.0090     | 0.05842     | 3.6745     | -0.0026     | 0.05064     | 5.9987     | -0.0021     | 0.05079     | 6.5810     |
| 2% SLP      | -0.0179     | 0.1129      | 5.1110     | -0.0053     | 0.1014      | 9.1548     | -0.0043     | 0.1016      | 9.5281     |
| 3% SLP      | -0.0268     | 0.1680      | 6.1924     | -0.0079     | 0.1523      | 10.7268    | -0.0065     | 0.1525      | 11.0850    |
| 4% SLP      | -0.0357     | 0.2224      | 6.9971     | -0.0105     | 0.2030      | 11.5288    | -0.0087     | 0.2033      | 11.8743    |
| 5% SLP      | -0.0445     | 0.2776      | 7.5706     | -0.0132     | 0.2529      | 12.2421    | -0.0109     | 0.2535      | 12.5755    |
Table 4 signifies the value of parameter indices. Table 4 reveals that these values with suggested IMO-tuned DMPID controller is less as compared to other techniques that reflect the superiority of the recommended controller.

7. Extension to multi-source interconnected power system

Here, the proposed control methodology is applied in a two-area multisource power system. Each area includes three categories of generating sources as hydro, gas and reheat thermal unit. The transfer function model of the multisource system is shown in Figure 18. The constraints of this system are referred from Mohanty et al. (2014) described in Appendix B. Three DMPID controllers are employed for each area to minimize the frequency and tie-line power deviations. The suitable values for the controller parameters are obtained using the IMO method with the application of 1% SLP in area 1. The optimum controller gains are listed in Table 5. The frequency deviation in area 1 ($\Delta f_1$), area 2 ($\Delta f_2$) and tie-line power deviation ($\Delta P_{tie}$) is shown in Figures 19–21.
Figure 13. Random loading pattern in area 1.

Figure 14. Frequency deviations in area 1 due to random loading in area 1.

Figure 15. Tie-line power deviation between areas 1 and 3 due to random loading in area 1.
respectively. From these figures, it is evident that the proposed control scheme is capable of successfully regulating frequency and tie-line power deviations as compared to other methods. Here, the results are compared with a recently published result like DE-tuned PID controller (Mohanty et al., 2014) to show the supremacy of the proposed methodology.
8. Conclusion

In this article, an effort has been made to develop a novel adaptive DMPID controller to address the AGC issues of power systems. Initially, IMO technique was employed to find out the finest parameters of the recommended DMPID controllers implemented in a three-area system. The addition of GRC and communication time delay increases the nonlinearities of the described system. The dynamic outcomes of the simulink model signified the dominance of the proposed control approach over the PID controller and bacteria foraging optimized conventional integral controller. The behavior of the investigated system was estimated in terms of settling time and maximum overshoot and least undershoots. Further, to prove the toughness of the offered method, various case studies were performed. Different case studies involved are the application of SLP in one area as well as in all areas, the variation of the SLP from 1% to 5% in a step of 1%, variation of system parameters and random variation of system loading. During these case studies, it was observed that the proposed system maintains stability regardless of the above-mentioned abnormalities. It was also demonstrated that the recommended control scheme is capable of compensating communication time delay and preserves its stability. The efficacy of the developed method is also proved by evaluating various performance indices like IAE, ITAE, ISE, and ITSE. These indices were compared with other methods to reflect the superiority of the proposed work. Finally,
implementation of this projected DMPID controller in another interconnected model (multi-source system) proved the flexibility of the proposed control technique.

**Funding**
The authors received no direct funding for this research.

**Author details**
Gayatri Mohapatra
E-mail: gayatrim79@gmail.com

Manoj Kumar Debnath
E-mail: mkd.odisha@gmail.com

ORCID ID: http://orcid.org/0000-0003-4752-7152

Krushna Keshab Mohapatra
E-mail: krushnakmohapatra@gmail.com

1 Department of Electrical Engineering, Siksha ‘O’ Anusandhan Deemed to be University, Bhubaneswar, Odisha 751030, India.

**Citation information**
Cite this article as: IMO-based novel adaptive dual-mode controller design for AGC investigation in different types of
Figure 21. Tie-line power deviation of multi-source system considering 1% SLP in area 1.
Gozte, H., & CengizTozmaciouglu, M. (2011). Automatic generation control application with craziness based particle swarm optimization in a thermal power system. International Journal of Electrical Power & Energy Systems, 33(1), 8–16. doi:10.1016/j.ijepes.2010.08.010

Jagatheesan, K., Anand, B., Samanta, S., Dey, N., Santhi, V., Ashour, A. S., & Balas, V. E. (2017). Application of flower pollination algorithm in load frequency control of multi-area interconnected power system with nonlinearity. Neural Computing and Applications, 28(1), 475–488. doi:10.1007/s00521-016-2361-1

Javidy, B., Hatamliou, A., & Mirjalili, S. (2015). Ions motion algorithm for solving optimization problems. Applied Soft Computing, 32, 72–79. doi:10.1016/j.asoc.2015.03.035

Khuntia, S. R., & Panda, S. (2010). Comparative study of different controllers for automatic generation control of an interconnected hydro-thermal system with generation rate constraints. Industrial Electronics, Control & Robotics (IECR), 2010 International Conference on Orissa, India. IEEE.

Khuntia, S. R., & Panda, S. (2012). Simulation study for automatic generation control of a multi-area power system by ANFIS approach. Applied Soft Computing, 12(1), 333–341. doi:10.1016/j.asoc.2011.08.039

Kundur, P. (1994). Power system stability and control. Vol. 7 N. J. Balu & M. G. Lauby. Eds. New York: McGraw-hill.

Liu, X., Zhang, Y., & Lee, K. Y. (2017). Coordinated distributed MPC for load frequency control of power system with wind farms. IEEE Transactions on Industrial Electronics, 64(6), 5140–5150. doi:10.1109/TIE.2016.2624882

Mohanty, B., Panda, S., & Hota, P. K. (2014). Controller parameters tuning of differential evolution algorithm and its application to load frequency control of multisource power system. International Journal of Electrical Power & Energy Systems, 54, 77–85. doi:10.1016/j.ijepes.2013.06.029

Mu, C., Tang, Y., & HaiBo, H. (2017). Improved sliding mode design for load frequency control of power system integrated an adaptive learning strategy. IEEE Transactions on Industrial Electronics, 64(8), 6742–6751. doi:10.1109/TIE.2017.2694936

Mudi, K. R., & Pal, R. N. (1999). A robust self-tuning scheme for PI-and PD-type fuzzy controllers. IEEE Transactions on Fuzzy Systems, 7(1), 2–16. doi:10.1109/91.746295

Nanda, J., Mishra, S., & Saikia, L. C. (2009). Maiden application of bacterial foraging-based optimization technique in multiarea automatic generation control. Power Systems, IEEE Transactions, 24(2), 602–609. doi:10.1109/TPWRS.2009.2016588

Ojaghi, P., & Rahmani, M. (2017). LMI-based robust predictive load frequency control for power systems with communication delays. IEEE Transactions on Power Systems, 32(5), 4091–4100. doi:10.1109/TPWRS.2017.2654453

Omar, M., Soliman, M., Ghany, A. A., & Bendary, F. (2013). Optimal tuning of PID controllers for hydrothermal load frequency control using ant colony optimization. International Journal on Electrical Engineering and Informatics, 5(3), 348–360. doi:10.15676/ieee.2013.5.3.8

Pappachen, A., & Peer Fathima, A. (2017). Critical research areas on load frequency control issues in a deregulated power system: A state-of-the-art-of-review. Renewable and Sustainable Energy Reviews, 72, 163–177. doi:10.1016/j.rser.2017.01.053

Rout, U. K., Sahu, R. K., & Panda, S. (2013). Design and analysis of differential evolution algorithm based automatic generation control for interconnected power system. Ain Shams Engineering Journal, 4(3), 409–421. doi:10.1016/j.asej.2012.10.010

Saikia, L. C., Mishra, S., Sinha, N., & Nanda, J. (2011). Automatic generation control of a multi area hydro-thermal system using reinforced learning neural network controller. International Journal of Electrical Power & Energy Systems, 33(4), 1101–1108. doi:10.1016/j.ijepes.2011.01.029

Singh, V. P., Kishor, N., & Samuel, P. (2017). Distributed multi-agent system-based load frequency control for multi-area power system in smart grid. IEEE Transactions on Industrial Electronics, 64(6), 5151–5160. doi:10.1109/TIE.2017.2668983

Wu, H., Tsakalis, K. S., & Heydt, G. T. (2004). Evaluation of time delay effects to wide-area power system stabilizer design. Power Systems, IEEE Transactions, 19(4), 1935–1941. doi:10.1109/TPWRS.2004.836272

Wu, H., Tsakalis, K. S., Heydt, G. T., Panda, S., & Narendra, K. Y. (2013). Automatic generation control of multi-area power system using multi-objective non-dominated sorting genetic algorithm-II. International Journal of Electrical Power & Energy Systems, 53, 54–63. doi:10.1016/j.ijepes.2013.04.003

Zeynelgil, H. L., Demiroren, A., & Sengor, N. S. (2002). The application of ANN technique to automatic generation control for multi-area power system. International Journal of Electrical Power & Energy Systems, 24(5), 345–354. doi:10.1016/S0142-0615(01)00049-7
Appendix A

Parameters of the three-area thermal system:

\[ f = 60 \text{ Hz}; R_1 = R_2 = R_3 = 2.4 \text{ Hz/p.u. MW}; B_1 = B_2 = B_3 = 0.425 \text{ p.u. MW/Hz}; T_{g1} = T_{g2} = T_{g3} = 0.08 \text{ s}; T_{r1} = T_{r2} = T_{r3} = 10 \text{ s}; K_1 = K_2 = K_3 = 0.5; H_1 = H_2 = H_3 = 5 \text{ s}; T_{t1} = T_{t2} = T_{t3} = 0.3 \text{ s}; K_{p1} = K_{p2} = K_{p3} = 120 \text{ Hz/p.u. MW}; T_{p1} = T_{p2} = T_{p3} = 20 \text{ s}; D_1 = D_2 = D_3 = 0.00833 \text{ p.u. MW/Hz}; T_{12} = T_{23} = T_{13} = 0.544; a_{12} = -1/2; a_{23} = -1/2; a_{13} = -1/4. \]

Appendix B

Parameters of the multi-source power system:

\[ f = 60 \text{ Hz}; R = 2.4 \text{ Hz/p.u. MW}; B_1 = B_2 = 0.4312 \text{ p.u. MW/Hz}; T_{s_{g1}} = 0.08 \text{ s}; T_r = 10 \text{ s}; K_g = 0.5; K_f = 0.5434; K_{t_{1}} = 0.32608; K_G = 0.130438; T_{G_{H}} = 0.2 \text{ s}; T_{B_{H}} = 28.75 \text{ s}; T_{w} = 5 \text{ s}; T_{w} = 1 \text{ s}; b_g = 0.05; c_g = 1; x_c = 0.6; y_c = 1; T_{c_{r}} = 0.01 \text{ s}; T_f = 0.23 \text{ s}; T_{c_{D}} = 0.2 \text{ s}; T_{w} = 11.49 \text{ s}; K_{w} = 68.9566; T_{D_{C}} = 0.2 \text{ s}; K_{D_{C}} = 1; T_{12} = 0.0433; a_{12} = 1. \]