ANT COLONY OPTIMIZATION TECHNIQUE OPTIMIZED CONTROLLER FOR FREQUENCY STABILIZATION OF AN ISOLATED POWER SYSTEM WITH NON-LINEARITY

by

Venkatachalam KUMARAKRISHNAN[a*], Govindaraj VIJAYAKUMAR[b], Ragupathi PRAKASH[c], and Siddhan SARAVANAN[c]

[a] Department of Electrical and Electronics Engineering, Paavai Engineering College, Namakkal, Tamil Nadu, India
[b] Department Electrical and Electronics Engineering, Sanjivani College of Engineering, Kopargaon, Maharashtra, India
[c] Department. Electrical and Electronics Engineering, Muthyammal Engineering College, Rasipuram, Tamil Nadu, India

Original scientific paper
https://doi.org/10.2298/TSCI221112247K

The load frequency control of a thermal power producing system, the ant colony optimization (ACO) approach adjusted proportional integral derivative (PID) controller is proposed. This work examines the single area thermal power system with /without generation rate constraint. For emergency situations, a PID controller is developed and used to regulate power system characteristics. This study uses the ACO method with the integral time absolute error objective function optimize controller gain values. In addition, the performance of the suggested approach is evaluated by introducing non-linearity components to the power-generating systems under study. Conventional, particle swarm optimization (PSO), and genetic algorithms (GA) approach tuned controller responses are compared with ACO. Fast settling with minimal peak and undershoots in the producing power supply of the system under emergency loading situations demonstrates the superiority of the proposed controller over competing controllers.

Key word: *frequency regulation, proportional integral derivative controller, frequency deviation, particle swarm optimization, frequency oscillation*

Introduction

The modernized power networks are interconnected and function with the typical values of frequency and tie-line power flow, according to the load request by the customer the power generation needs control. At the time of generation switching and load demand the power system should operate at the standard values this is the ultimate aim of load frequency control (LFC), [1, 2].

Numerous scholars have addressed the following LFC scheme of power systems with controllers and optimization techniques: Kumarakrishnan *et al*. [3] has proposed PSO-PID controller for LFC of multiple sources power network with non-renewable energy and thermal power plant. Boopathi *et al.* [4] investigated a single area micro gird incorporated with a thermal

* Corresponding author, e-mail: kumarakrishnan2002@gmail.com

power system by implementing PSO-PID controller for LFC. Jagatheesan *et al.* [5] a microgrid (thermal + PV + wind) is investigated for LFC by GWO-PID controller. A single area thermal power unit inspected by Davtalab *et al.* [6] implemented a fuzzy controller for interconnected power network LFC. A cascaded fuzzy PD-PI controller is employed with GOA Tripathy *et al.* [7], Saurabh *et al.* [8] investigated a single and grid-connected thermal power system by using fractional order PID (FOPID) which is tuned by moth flame optimization (MFO) algorithm. The FLC is examined as a three-area thermal, PV system, also the result was compared with PI controller, Revathi and Kumar [9]. An interlinked thermal power system incorporated with electrical vehicle (EV) model is undergone automatic generation control (AGC) by adopting the DISCO participation matrix method, Prajapati *et al.* [10].

A QODA-tuned PID controller is appointed to regulate the oscillation in the frequency of a grid-connected power network, Vedik *et al.* [11], and the impact of an isolated HPS with RES and ESD system is involved for frequency, Mudi *et al.* [12]. The PSO-PID regulator is implemented in single area multi sources power network LFC by Kumarakrishnan *et al.* [13]. In a single area, nuclear power plant inspected by ACO-PID the proposed controller provides a better improvement over the conventional method for different cost functions, Dhanasekaran *et al.* [14]. Ali *et al.* [15] investigated an interconnected power network with non-linear constraints by sooty terns approach to optimal MPC.

A single area thermal power network is investigated by fractional order IMC, Saxena [16], FOPID in Sondhi and Hote [17], SPSO optimized PID implemented by Jagatheesan *et al.* [18], FLC is designed for thermal power network, and the response compared with some other literature result in Fagna [19]. Alhelou *et al.* [20] is suggested WDO algorithm proposed for PID controller optimization examine multi-area thermal power network LFC considering GRC and GDB non-linearities. Panwar *et al.* [21] is inspected an interconnected hydro power plant with an energy storage unit by implementing BFO-PSO technique tuned PID controller. Jagatheesan and Anand [22] utilized classical controllers for LFC of interlinked thermal power networks with GRC. The behavior of the proposed controller to various cost functions is thoroughly examined. In Tasnin *et al.* [23], FOPI-FOPD cascade controller is used for the AGC of a geothermal power plant. The PSO-optimized integral controller is used for single and multi-area, respectively, Tavakoli *et al.* [24]. Elephant herding optimization technique optimized PID regulator developed by Sambariya and Fagna [25] for thermal power plant LFC.

For the AGC problem in Acharyulu *et al.* [26] by applied MFO optimized PID controller for an isolated thermal power plant, in Nandi *et al.* [27] two area hydro plant, ICA tuned PID controller developed for AGC of a power grid, Shabani *et al.* [28]. In the early period of the ACO evolution the author utilized for the power system problem solving, ACO optimized PID controller utilized for hydro thermal power plant by Omar *et al.* [29], and the result was compared with conventional methods. The literature survey gives details about the implementation and effectiveness of the optimization techniques to enhance the secondary controller gain, and how the optimized controller minimizes the oscillation and maintains the stability of supply in the power grid line. Also, the majority of the research people studied and analyzed the response of the proposed controller for the thermal power system. The thermal power system is one of the main power sources.

Contribution of the article

Electricity is one of the factors for the country's development. In the world, more than 75% of countries are developing countries. Those countries mostly depend on electricity, thermal is the major power source for those counties. From the literature review, many of the researchers developed and discussed the performance of the thermal power plant under some specific scenario. In this article, the thermal power plant is analyzed under a different scenario like with/without reheater and with/without generation rate constraint (GRC) by implementing ACO technique tuned PID controller. This research gives a complete analysis of the thermal power system stability with the support of the PID controller.

Significance of the article

The proposed work is carried out with the following key points:
- To construct a PID controller to find solution for LFC of thermal with non-linearity.
- To find optimal gain parameters using conventional, PSO, GA, and ACO techniques.
- To Probe the proposed model by applying optimal gain values.
- To find the improvement of ACO over conventional, PSO, and GA.

Modelling of the investigated power system

The proposed research work four different models (System 1 – SANRH, System 2 – SANRH with GRC, System 3 – SARH, System 4 – SARH with GRC) of an isolated area thermal power system including of governor with turbine, turbine with reheater, and turbine GRC is investigated for LFC by employing optimized PID controller. The proposed system is exposed in figs. 1-4. System 1 (SANRH) has the governor and steam turbine block without a reheater and GRC is shown in fig. 1. The mathematical expression of the aforementioned three models is dispatched in tab. 1. *Appendix* has the nominal parameters of the developed model. The modelling of the system is studied by Choudhary *et al.* [30]. The study is carried out by applying 1% SLP to the control area.

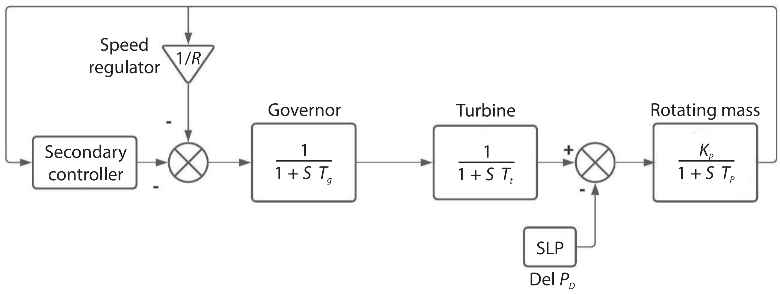

Figure 1. Single area non-reheater (SANRH) thermal power system

The proposed System 2, (SANRH with GRC), which is includes GRC with the System 1 is shown in fig. 2.

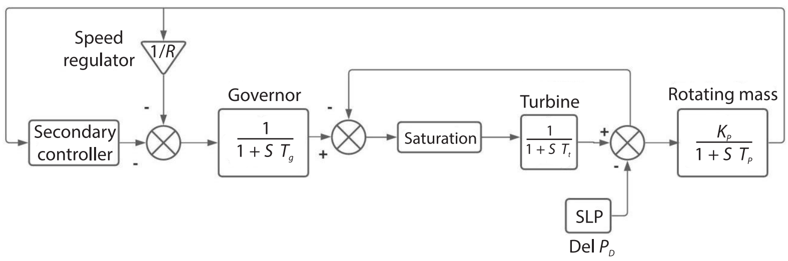

Figure 2. Single area non-reheater (SANRH) thermal power system with GRC

The proposed System 3 (SARH without GRC) is shown in fig. 3, it includes of thermal power plant with reheater without GRC.

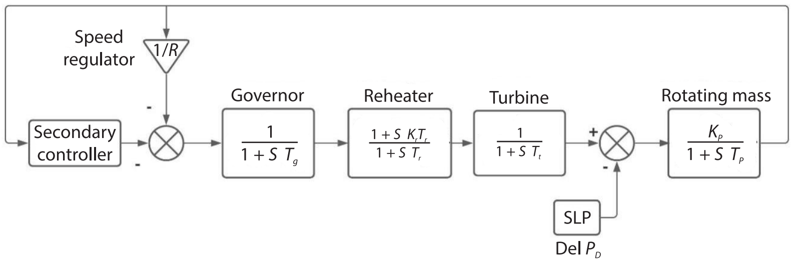

Figure 3. Single area thermal power system with reheater (SARH)

The proposed power System 4 (SARH with GRC) is demonstrated in fig. 4, which is incorporation of GRC with system 3.

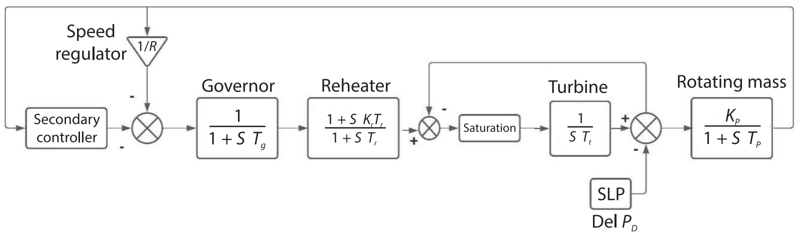

Figure 4. Single area re- heater (SARH) thermal power system with GRC (SARH with GRC)

Table 1. Mathematical expression of investigated power system

Component	Expression
Steam turbine without GRC	$\frac{1}{1+ST_t}$
Steam turbine with GRC	$\frac{1}{ST_t}$
Governor	$\frac{1}{1+ST_g}$
Reheater	$\frac{1+SK_rT_r}{1+ST_r}$
Rotating mass	$\frac{K_P}{1+ST_P}$
Speed regulator	$\frac{1}{R}$

where T_t, T_g, T_r, and T_P are represented as turbine, governor, reheater, and power system time constants, respectively. The K_r and K_P are denoted as reheater and power system gain constants. The R stands for the primary regulator gain constant.

Controller strategy and objective function

For industrial application derivative controller alone is not advisable because noise in the feedback signal is too high. So, an incorporated controller is much need to control the noise in the output. Especially in the power system applications, the PID controller is mostly involved, because of the effectiveness and easy to applicable. It also responds to feedback signals as quickly as possible to achieve the desired results. An error signal generated with respected to the area control error (ACE). A suitable linear combination of frequency and tie line power changes for area is known as the ACE. The mathematical representation of PID controller is mentioned in eq. (1). The K_I, K_P, and K_D are the controller gains. Figure 5 shows a common PID controller structure:

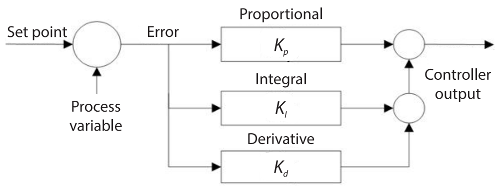

Figure 5. Structure PID controller

$$G_{\text{PID}} = K_P + \frac{K_I}{S} + S\,K_D \tag{1}$$

The cost function must be chosen carefully in order to reduce oscillation and other factors in the power network's frequency deviation under an emergency loading circumstance. In this proposed study, the ITAE cost function is involved in the process tuning of the controller gain. Equation (2) dispatches the ITAE expression. Where t_{sim} is the simulation time and J is the performance index:

$$J_{\text{ITAE}} = \int_0^{t_{\text{sim}}} \left(del\,F\right) t\,\mathrm{d}t \tag{2}$$

Tuning methodology

In this section suggested PID controller is demonstrated with developed Simulink models in section *Modelling of the investigated power system*, from each computation method (conventional, PSO, ACO) the optimized controller gain parameters are acquired.

Conventional tuning method

The conventional (trial and error) method is implemented to optimize the auxiliary controller gain parameters for the LFC problem of the proposed power network. This method is one of the traditional methods to acquire optimal controller gain constants. In this method, random numbers are applied to find optimal gain parameter values based on the ITAE objective function. Tuning procedure of the conventional method is:

Step 1. Find optimal K_I at K_P and K_D = 0.

Step 2. Fix K_I, find K_P at K_D = 0.

Step 4. Fix K_I and K_P, find K_D.

By conducting the previous steps, fine-tuned optimal gain parameters are collected and tabulated in tab. 2. The performance index curve is shown in figs. 6-9.

Table 2. Tuned gain parameters of conventional method optimized PID controller

System / Gain value	K_P	K_I	K_D	J_{ITAE}
NRH without GRC	0.06	0.3	0.01	0.07047
NRH with GRC	0.04	0.3	0.05	0.07233
RH without GRC	2	0.35	0.02	0.2145
RH with GRC	0.35	2.5	0.06	0.1497

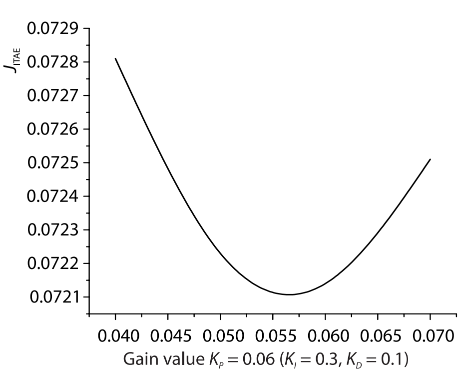

Figure 6. The *J* curve for NRH without GRC system

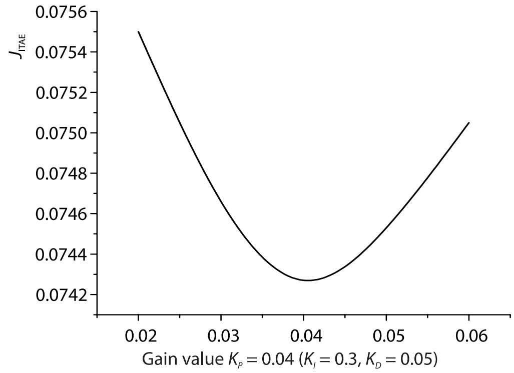

Figure 7. The *J* curve for NRH with GRC system

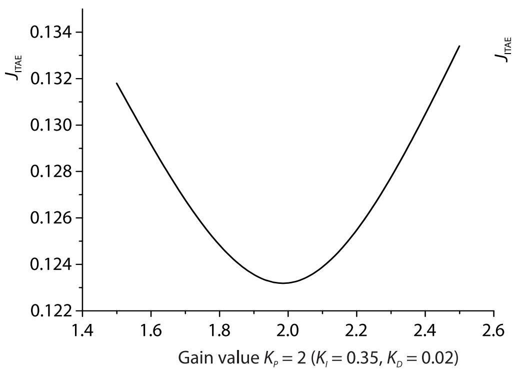

Figure 8. The *J* curve for RH without GRC system

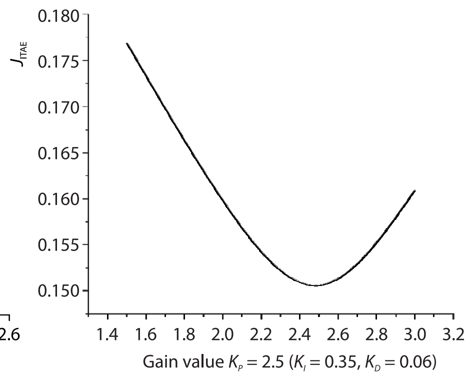

Figure 9. The *J* curve for RH with GRC system

Particle swarm optimization technique

The PSO is a method developed by Kennedy and Eberhart [31]. The author Millonas [32] uses the team swarm in his paper to construct and express his models for artificial life. Five essential swarm intelligence principles:

- *The proximity of principle*: Computations of population space and time.
- T*he principle of quality*: The populace should react to the situation's quality aspects.
- *Diverse response principle*: Narrow channels should not be followed by the general public.
- *Stability principle*: At all times, the people should not change its behaviour.
- *Adaptability principle*: The population must adapt to a shift in behaviour mode as a function of computational time.

The number of dimensional space calculations passed throughout the time of computation. From the aforementioned five principles, population quality is separated as pbest and gbest. The factor P_{best} changes its position for each computation, but the G_{best} does not change to bring stability. The particles in the population are massless and volume less, they are called points. The points are looked like the speeds and accelerations are more properly applicable to objects, even though each is described to have an arbitrary effect of small weight and volume. Figure 10 depicts the PSO technique's functional flow chart.

Optimal controller gain parameters are obtained from PSO technique to minimize the oscillation and bring the system response to stability, during predicament salutation. Obtained gain parameter constants are reported in tab. 3.

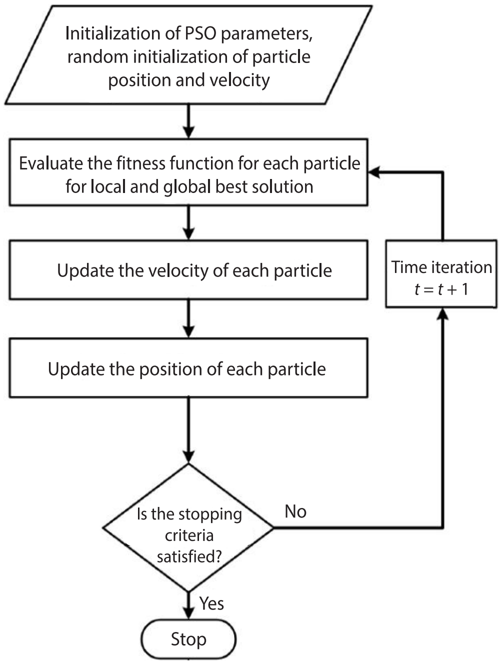

Figure 10. The PSO technique functional flow chart

Ant colony optimization technique

The foraging behavior of ant species inspires the optimization of the ant colony. Using these ants' pheromones to indicate any favorable marks on the field. The path that all members of the colony should follow. Optimization of the ant colony uses a related mechanism to solve problems of optimization initially. The ants are always found an optimized path for searching for food. The concentration of the pheromone is determined by the value and quantity of food along the route. For more amount of food, ants will evaporate much amount of pheromone. Ants in the colony always follow the highly concentrated pheromone path. This algorithm was first developed by Dorigo and Gambardella [33] for solving a salesman traveling path problem. The recommended controller gain parameter values are optimized using the ACO approach for the SAPS under investigation. The optimized gain parameters are reported in tab. 4. The ACO algorithm flow diagram is shown in fig. 11.

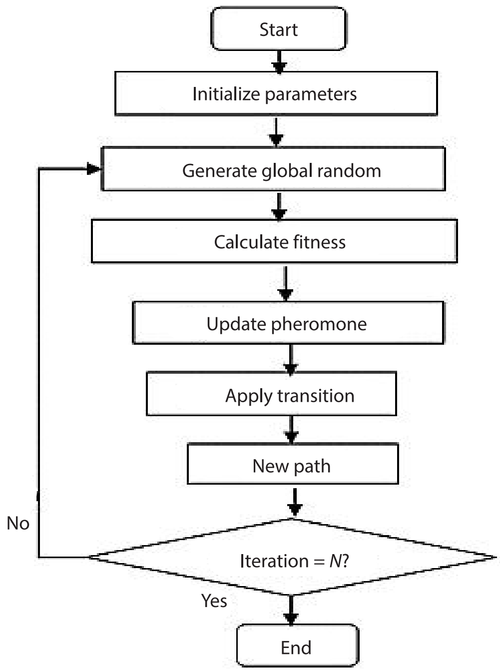

Figure 11. The ACO technique algorithm flow diagram

Table 3. Optimal controller gain parameters from PSO technique

System/Gain value	K_P	K_I	K_D	J_{ITAE}
NRH without GRC	8.1472	7.5774	2.7603	0.00238
NRH with GRC	6.7844	8.7253	6.6719	0.08403
RH without GRC	8.1472	7.5774	2.7603	0.01126
RH with GRC	6.7844	8.7253	6.6719	0.01323

In the ACO optimization technique the following represents are utilized for the computation process. Ants (K) – any possible solution, population (N) – group of all ants, search space [*lb, ub*] – all possible solutions to the problem with lower bound and upper bound, pheromone trail – τ, scaling parameters – ξ, and evaporation rate – ρ. With the previous parameters ACO technique is optimize the controller gain parameters as per the following procedure.

Procedure of ACO:

Step 1. Initialization:

– Initialize all the parameters and amount of pheromone rate, τ.

Step 2: Build tour:

– The probability to select discrete values of variables:

$$P_j^k = \frac{\tau_j}{\sum_{j=1}^{m} \tau_j}$$

– Find the cumulative probability range associate with different values based on its probabilities.
– Generate, N, random number, r in range (0, 1) one for each ant.

Step 3. Update pheromone:

– Evaluate the objective function values of each ant.
– Determine the best and worst objective function values.
– Best ant pheromone value is replaced to the worst ant pheromone

$$\tau_j^{\text{new}} \leftarrow \tau_j^{\text{old}} + \sum_k \Delta \tau_j^k .$$

Step 4. Termination:

– Algorithm repeated until the maximum number of iterations is reached.

Parameters required for the optimization:

The number of ants = 100, pheromone rate = 0.06, evaoration rate = 0.95, maximum tour = 100, upper bound, ub = 1 and lower bound, lb = 0.

Table 4. Optimal controller gain parameters from ACO technique

System/Gain value	K_P	K_I	K_D	J_{ITAE}
NRH without GRC	0.38	0.85	0.19	0.02283
NRH with GRC	0.53	0.98	0.2	0.0168
RH without GRC	0.93	1	0.13	0.0829
RH with GRC	0.97	0.97	0.17	0.08524

Result and discussion

The demonstration and the result of proposed power network models with different optimization methods are discussed in this section. Case 1: result comparison open loop response, conventional method, PSO, GA, and ACO method optimized PID regulator performance with the proposed power network (SANRH with/without GRC). Case 2: result comparison open loop response, conventional method, PSO, GA, and ACO method optimized PID regulator performance with the proposed power network (SARH with/without GRC).

Case 1. Performance assessment of conventional, PSO, GA, and ACO optimized PID controller.

The suggested SANRH without the GRC power system model is simulated in MATLAB 2016a version by giving 1% load distribution the control area. The controller's gain parameters were optimized by the conventional method, PSO, GA, and ACO methods. By applying optimal controller gain parameters, the system frequency comes stable and the oscillation is controlled by the impact of the secondary controller. Table 4 displays the optimal frequency response characteristics. Figure 12 depicts the graphical comparison.

The ACO-PID controller regulates the system frequency oscillation and settles the oscillation quicker than other optimization method-tuned controllers in the performance analysis of conventional, PSO, GA, and ACO-optimized PID controllers. Figure 12 and tab. 5 indicate the improvement of the ACO-PID in teams of a quick frequency oscillation settling the oscillation (conventional: 12 seconds > GA:6.8 seconds > PSO:6.4 seconds > ACO:6 seconds).

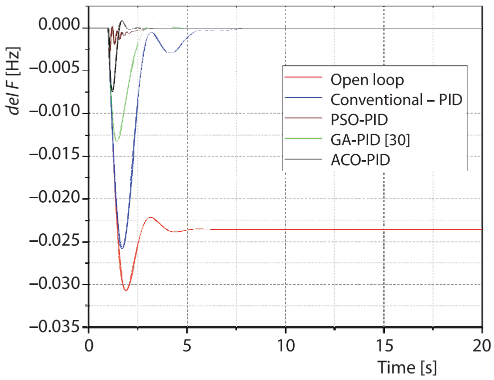

Figure 12. The *del F* response comparison of open loop, PID controller based conventional, PSO, GA, and ACO method

Table 5. Optimized parameters of SANRH without GRC power system

Optimized parameters/controller	Settling time [second]	Overshot [Hz]	Undershoot [Hz]
Conventional – PID	12	0	0.0258
PSO-PID	6.4	$2.35 \cdot 10^{-4}$	$2.95 \cdot 10^{-3}$
GA-PID [30]	6.8	$10.5 \cdot 10^{-4}$	0.025
ACO-PID	6	$5.5 \cdot 10^{-4}$	0.0133

A bar chart is confirming the improvement once again, bar chart conventional, PSO, GA, and ACO-PID is shown in fig. 13. Bar chart comparison shows that the ACO-PID controller for the proposed system provides the improved response in terms of fast settling time over conventional, GA, and PSO-tuned PID controller.

Without the impact of GRC in the proposed model (SANRH) result were analysed, the non-linearity constrains (GRC) is applied with the proposed system ±0.5 p.u/MW. Result comparison is given in fig. 14. Table 6 reports optimum parameters derived from the response.

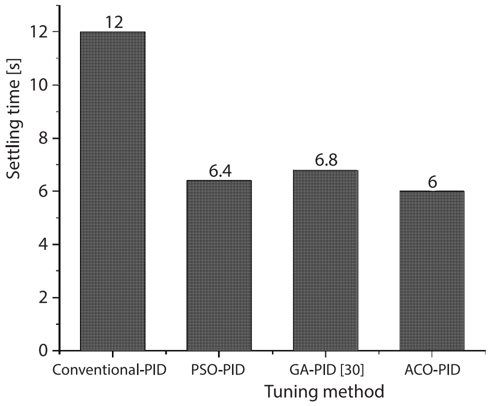

Figure 13. Comparison of traditional, PSO, GA, and ACO-PID controllers in terms of settling time

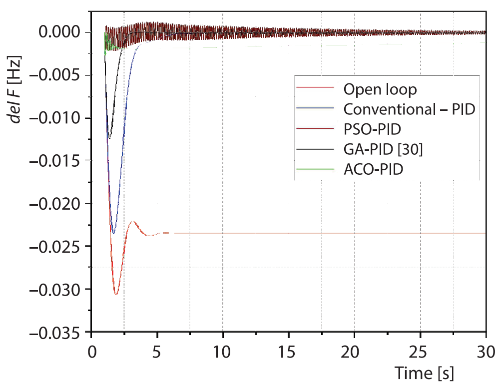

Figure 14. The *del F* response comparison of open loop, conventional, PSO, GA, and ACO-PID controller

The performance response analysis from fig. 14 and tab. 6 is evident that ACO-PID regulator controls the frequency oscillation during unexpected load demand occurs. For the same power network, the PSO optimization method response takes more time to attain stability, and also, oscillation is high. A bar chart in fig. 15 is used to confirm the supremacy of the proposed technique-optimized controller. The settling time improvement of the proposed controller (PSO:120 seconds > GA:40 seconds > conventional: 9 seconds > ACO: 6 seconds).

Case 2. Performance comparison of open loop, conventional, PSO, and ACO-PID controller with SARH with/without GRC system.

Table 6. Optimized parameters of SANRH with GRC power system

Optimized parameters/controller	Settling time [second]	Overshot [Hz]	Undershoot [Hz]
Conventional – PID	9	0	0.0235
PSO-PID	120	$1.25 \cdot 10^{-3}$	$2.15 \cdot 10^{-3}$
GA-PID [30]	40	0	0.0025
ACO-PID	6	$0.1 \cdot 10^{-3}$	0.0124

By using conventional, PSO, and ACO technique-optimized controller gain parameters, the proposed controller is demonstrated with the SARH system in MATLAB 2016a version by applying 1% SLP. The result is compared with open loop, conventional, PSO, GA, and ACO methods tuned PID controller simulation results. The result comparison is given in fig. 16. Also, the corresponding nominal time domain parameters are dispatched in tab. 7.

Figure 16 depicts the response of the suggested system in open loop, the conventional method and frequency response, the PSO method response, GA method response, and the ACO technique output response of the developed power network model.

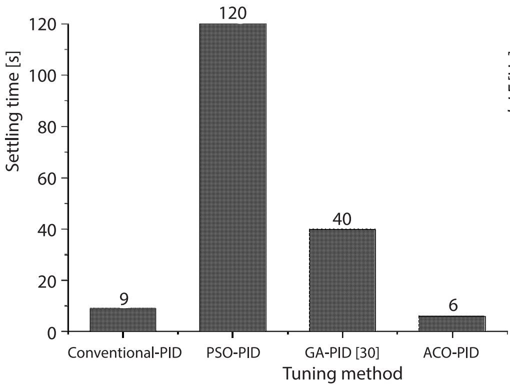

Figure 15. Settling time bar chart assessment of conventional, PSO, GA, and ACO technique optimized PID controller

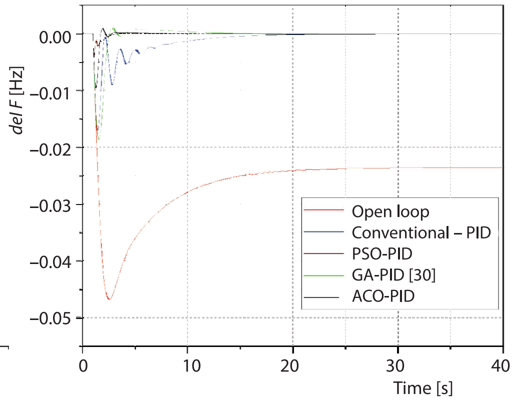

Figure 16. The *del F* response of comparison of open loop, conventional, PSO, GA, and ACO tuned PID controller for SARH without GRC

Table 7. Optimized parameters of SARH power system from fig. 16

Optimized parameters/controller	Settling time [second]	Overshoot [Hz]	Undershoot [Hz]
Conventional – PID	28	0	0.017
PSO-PID	24	$1.5 \cdot 10^{-4}$	$4.3 \cdot 10^{-3}$
GA-PID [30]	25	$2.0 \cdot 10^{-4}$	0.017
ACO-PID	22	$1 \cdot 10^{-3}$	0.0186

From fig. 16 and tab. 7, it is evident that ACO-PID controller is shown improvement in response, like quick settling of oscillation and minimized deviation (peak overshoot and peak undershoot) over the conventional, PSO method, and GA method. A bar chart for settling time comparison of conventional and PSO technique tuned controller performance for the proposed power network (SARH without GRC). Bar chat assessment is given in fig. 17, it shows ACO-PID control the oscillation of frequency quickly than over other methods tuned PID controller. The settling time improvement of the proposed controller (conventional: 28 seconds > GA:25 seconds > PSO:24 seconds > ACO: 22 seconds).

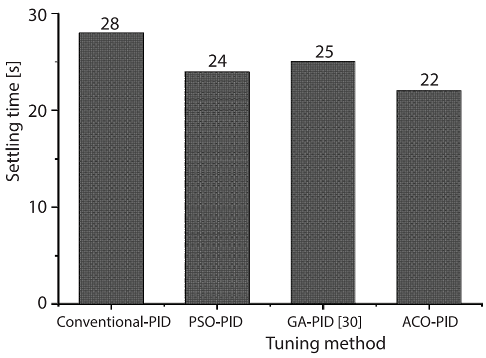

Figure 17. Settling time bar chart comparison of open loop response, conventional, PSO, GA, and ACO-PID controller with SARH without GRC

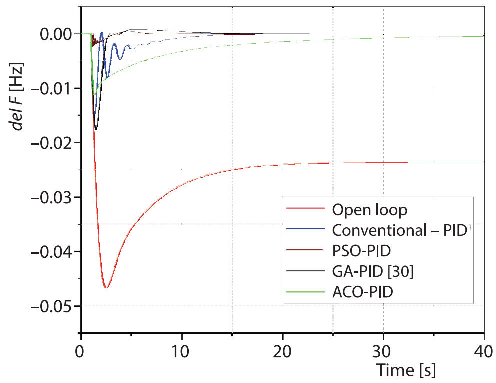

Figure 18. The *del F* response of comparison of open loop, conventional, PSO, GA, and ACO tuned PID controller for SARH with GRC

The generation ratio constraint component is implemented in the proposed SARH power network for analysis of the LFC problem. The effect of GRC on the proposed power network is to suppress oscillations and preserve system response stability. GRC values are ±0.5 p.u/MW. The frequency response of the power network (SARH) with GRC is analyzed with a graph which is shown in fig. 18. Corresponding optimized numerical parameters from fig. 18 are reported in tab. 8.

Table 8. Optimized parameters of SARH power system from fig. 18

Optimized parameters/controller	Settling time [second]	Overshot [Hz]	Undershoot [Hz]
Conventional – PID	35	$0.4 \cdot 10^{-3}$	0.015
PSO-PID	27	$5 \cdot 10^{-4}$	$2.7 \cdot 10^{-3}$
GA-PID [30]	47	$0.5 \cdot 10^{-3}$	0
ACO-PID	26	$0.8 \cdot 10^{-3}$	0.0175

In fig. 18 the ACO-PID controller performance is shows that as improved when compared with conventional and PSO-PID controller and GA-PID controller by fast settling and minimal peak values. The settling time improvement of the proposed controller (GA: 47 seconds > conventional: 35 seconds > PSO: 27 seconds > ACO: 26 seconds).

A bar chart assessment is used as evidence for the supremacy of the ACO-PID controller for LFC of the suggested power network. The settling time of the conventional, PSO, GA, and ACO tuning methods is comprised in fig. 19.

From the bar chart comparison, the ACO-PID controller has improved response over conventional, PSO-PID controller, and GA-PID controller with fast settling time of the system frequency during emergency conditions. The improvement of the proposed controller over other control technique based on settling is dispatched in tab. 9.

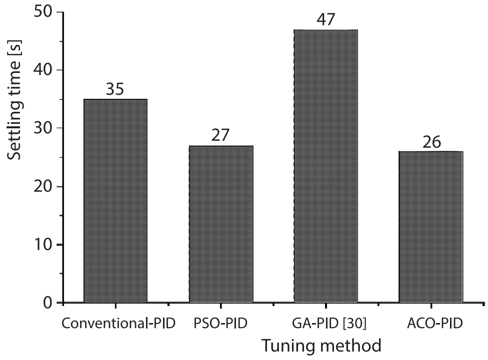

Figure 19. Settling time comparison of conventional, PSO, GA, and ACO tuning methods

Table 9. Improvement of the ACO-PID controller over conventional, PSO, and GA [30]

Model/Optimization technique	ACO over conventional method [%]	ACO over PSO [%]	ACO over GA [3] [%]
SANRH without GRC	100	6.6	13.3
SANRH with GRC	50	1900	600
SARH without GRC	27.2	9.09	13.63
SARH with GRC	34.6	3.84	80.7

Conclusion

To tackle the LFC problem, a section of the thermal power network is created and studied using various scenarios. The proposed power network is implemented as an isolated thermal power system with or without GRC. Conventional, PSO, GA, and ACO method-optimized controllers are applied to each of the four classes of system models. The frequency responses of open loop, conventional, PSO, and GA approaches are compared to demonstrate the capacity of the ACO optimization technique. The output response of the ACO-PID regulator for non-reheater thermal power networks with/without GRC regulates oscillation and stabilizes it in 6 seconds. With and without GRC, a reheated thermal system stabilizes the oscillation in 22 seconds and 26 seconds, respectively. In conclusion, the recommended ACO optimization approach outperforms previously stated optimization strategies in all scenarios.

Appendix

The T_t = 0.3 second, R = 2.4, K_r = 0.5, T_r = 10 seconds, T_g = 0.08 seconds, K_P = 120, and T_P = 20 seconds.

Over all MATLAB model of the proposed power system.

Authorship contribution statement

Kumarakrishnan V: Model development, Writing– original draft. Vijayakumar G: Validation, Writing – review & editing. Prakash R: Methodology, Data curation, Software tool support. Saravanan S: Visualization, Investigation.

Nomenclature

del F – frequency deviation
T_r – reheater time constant
K_I – integral gain
T_t – turbine time constant
K_D – derivative gain
T_g – governor time constant
T_P – power system time constant
K_r – reheater gain constant
K_P – power system gain constant
R – speed regulator constant
t_{sim} – simulation time

Acronyms

ACE – area control error
ACO – ant colony optimization
AGC – automatic generation control
BFO – bacterial foraging optimization
ESD – energy storage devices
EV – electrical vehicle
FLC – fuzzy logic control
FOPID – fractional order PID
GDB – generation dead band
GOA – grasshopper optimization algorithm
GRC – generation rate constrain
GWO – grey wolf optimization
HPS – hybrid power systems
ITAE – integral time absolute error
LFC – load frequency control
MFO – moth flame optimization
MPC – model predictive control
PID – proportional integral derivative
PSO – particle swarm optimization
QODA – quasi-oppositional dragonfly algorithm
SARH – single area reheated
SANRH – single area non-reheated
SLP – step load participation
SPSO – sliced particle swarm optimization
WDO – wind driven optimization

Reference

[1] Elgerd, O. I., *Electric energy Systems Theory: An Introduction*, McGraw-Hill, New York, USA, 1982
[2] Nagrath, J., Kothari, D. P., *Power System Engineering*, Tata Mc-Graw Hill Publishing Company Limited, New Delhi, India, 1994
[3] Kumarakrishnan, V., *et al*., The PSO Optimum Design-PID Controller for Frequency Management of Single Area Multi-Source Power Generating System, In Contemporary Issues in Communication, *Cloud and Big Data Analytics*, *662* (2022), Dec., pp. 373-383

[4] Boopathi, D., *et al*., Performance Estimation of Frequency Regulation for a Micro-Grid Power System Using PSO-PID Controller, *International Journal of Applied Evolutionary Computation*, *12* (2021), 2, pp. 36-49

[5] Jagatheesan, K., *et al.*, December, Frequency Stability Analysis of Microgrid Interconnected Thermal Power Generating System with GWO Tuned PID Controller, *Proceedings*, 9th IEEE International Conference on Power Systems (ICPS), Kharagpur, India, 2021, pp. 1-5

[6] Davtalab, S., *et al.*, Optimized Intelligent Coordinator for Load Frequency Control in a Two-Area System with PV Plant and Thermal Generator, *IETE Journal of Research*, *68* (2022), 5, pp. 3876-3886

[7] Tripathy, D., *et al*., A Novel Cascaded Fuzzy PD-PI Controller for Load Frequency Study of Solar-Thermal/Wind Generator-Based Interconnected Power System Using Grasshopper Optimization Algorithm, *The International Journal of Electrical Engineering and Education*, *60* (2020), Suppl. 1, pp. 40-48

[8] Saurabh, K., *Get al*., Fractional Order Controller Design for Load Frequency Control of Single Area and Two Area System, *Proceedings*, 7th International Conference on Signal Processing and Integrated Networks (SPIN), Noida, India, 2020, pp. 531-536

[9] Revathi, D., Mohan Kumar, G., Analysis of LFC in PV-Thermal-Thermal Interconnected Power System Using Fuzzy Gain Scheduling, *International Transactions on Electrical Energy Systems*, *30* (2020), 5

[10] Prajapati, Y. R., *et al*., Load Frequency Control Under Restructured Power System Using Electrical Vehicle as Distributed Energy Source, *Journal of The Institution of Engineers (India): Series B*, *101* (2020), 4, pp. 379-387

[11] Vedik, B., *et al*., Renewable Energy-Based Load Frequency Stabilization of Interconnected Power Systems Using Quasi-Oppositional Dragonfly Algorithm, *Journal of Control, Automation and Electrical Systems*, *32* (2020), Oct., pp. 227-243

[12] Mudi, J., *et al.*, Frequency Stabilization of Solar Thermal-Photovoltaic Hybrid Renewable Power Generation Using Energy Storage Devices, Iranian Journal of Science and Technology, *Transactions of Electrical Engineerin*g, *45* (2020), Sept., pp. 597-617

[13] Kumarakrishnan, V., *et al*., Optimized PSO Technique Based PID Controller for Load Frequency Control of Single Area Power System, *Solid State Technology*, *63* (2020), 5, pp. 7979-7990

[14] Dhanasekaran, B., *et al*., Ant Colony Optimization Technique Tuned Controller for Frequency Regulation of Single Area Nuclear Power Generating System, *Microprocessors and Microsystems*, *73* (2020), 102953

[15] Ali, H. H., *et al*., Optimal Model Predictive Control for LFC of Multi-Interconnected Plants Comprising Renewable Energy Sources Based on Recent Sooty Terns Approach, *Sustainable Energy Technologies and Assessments*, *42* (2020), 100844

[16] Saxena, S., Load Frequency Control Strategy Via Fractional-Order Controller and Reduced-Order Modelling, *International Journal of Electrical Power and Energy Systems*, *104* (2019), Jan., pp. 603-614

[17] Sondhi, S., Hote, Y. V., Fractional Order PID Controller for Load Frequency Control, *Energy Conversion and Management*, *85* (2014), Sept., pp. 343-353

[18] Jagatheesan, K., *et al*., Design of Proportional-Integral-Derivative Controller Using Stochastic Particle Swarm Optimization Technique for Single-Area AGC Including SMES and RFB Units, *Proceedings*, 2nd International Conference on Computer and Communication Technologies, Chengdu, China, 2016, pp. 299-309

[19] Fagna, R., Load Frequency Control of Single Area Thermal Power Plant Using Type 1 Fuzzy Logic Controller, *Science Journal of Circuits, Systems and Signal Processing*, *6* (2017), 6, pp. 50-56

[20] Alhelou, H. H., *et al*., Wind Driven Optimization Algorithm Application Load Frequency Control in Interconnected Power Systems Considering GRCAnd GDB Non-Linearities, *Electric Power Components and Systems*, *46* (2018), 11-12, pp. 1223-1238

[21] Panwar, A., *et al*., Frequency Stabilization of Hydro-Hydro Power System Using Hybrid Bacteria Foraging PSO with UPFC and HAE, *Electric Power Systems Research*, *161* (2018), Aug., pp. 74-85

[22] Jagatheesan, K., Anand, B. The AGC of Multi-Area Hydro-Thermal Power Systems with GRC Non-Linearity and Classical Controller, *Journal of Global Information Management*, *26* (2018), 3, pp. 11-24

[23] Tasnin, W., *et a*l., Effect of Geothermal and Other Renewables on AGC of an Interconnected Thermal System, Innovations in Infrastructure, in: *Advances in Intelligent Systems and Computing*, Springer, New York, USA, 2019, vol. 575, pp. 481-491

[24] Tavakoli, M., *et al*., Load-Frequency Control in A Multi-Source Power System Connected to Wind Farms through Multi Terminal HVDC Systems, *Computers and Operations Research*, *96* (2018), Aug., pp. 305-315

[25] Sambariya, D. K., Fagna, R., A Novel Elephant Herding Optimization Based PID Controller Design for Load Frequency Control in Power System, *Proceedings*, International Conference on Computer, Communications and Electronics, Jaipur, India, 2017, pp. 595-600

[26] Acharyulu, B. V. S., *et al*., Comparative Performance Analysis of PID Controller With Filter For Automatic Generation Control With Moth-Flame Optimization Algorithm, Applications of Artificial Intelligence Techniques in Engineering, in: *Advances in Intelligent Systems and Computing*, Springer, New York, USA, 2019, vol. 698, pp. 509-518
[27] Nandi, M., *et al*., Moth-Flame Algorithm for TCSC-and SMES-Based Controller Design in Automatic Generation Control of a Two-Area Multi-unit Hydro-power System, *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, *44* (2019), Dec., pp. 1173-1196
[28] Shabani, H., *et al.*, A Robust PID Controller Based on Imperialist Competitive Algorithm for Load-Frequency Control of Power Systems, ISA Transactions, *52* (2013), 1, pp. 88-95
[29] Omar, M., *et al*., Optimal Tuning of PID Controllers for Hydrothermal Load Frequency Control Using Ant Colony Optimization, International Journal on Electrical Engineering And Informatics, *5* (2013), 3, 348
[30] Choudhary, R., *et al.*, Automatic Generation Control For Single Area Power System Using GNA Tuned PID Controller, *In Journal of Physics: Conference Series*, *1478* (2020), 012011
[31] Kennedy, J., Eberhart, R., Particle Swarm Optimization, *Proceedings*, ICNN'95-International Conference on Neural Networks, Perth, Australia, 1995, Vol. 4, pp. 1942-1948
[32] Millonas, M. M., Swarms, Phase Transitions, and Collective Intelligence, *Proceedings*, Santa Fe Institute Studies in the Sciences of Complexity-Proceedings, Santa Fe, N. Mex., USA, 1992
[33] Dorigo, M., Gambardella, L. M., Ant Colony System: A Cooperative Learning Approach to the Traveling Salesman Problem, *IEEE Transactions on Evolutionary Computation*, *1* (1997), 1, pp. 53-66

Paper submitted: November 12, 2022
Paper revised: September 15, 2023
Paper accepted: October 3, 2023