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Chaos Algorithm versus Traditional and Optimal Approaches for Regulating Line Frequency of Steam Power System

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Abstract- Load Frequency Control (LFC) is a basic control strategy for proper operation of the power system. It ensures the ability of each generator in regulating its output power in such way to maintain system frequency and tie-line power of the interconnected system at prescribed levels. This article introduces comprehensive comparative study between Chaos Optimization Algorithm (COA) and optimal control approaches, such as Linear Quadratic Regulator (LQR), and Optimal Pole Shifting (OPS) regarding the tuning of LFC controller. The comparison is extended to the control approaches that result in zero steady-state frequency error such as Proportional Integral (PI) and Proportional Integral Derivative (PID) controllers. Ziegler-Nicholas method is widely adopted for tuning such controllers. The article then compares between PI and PID controllers tuned via Ziegler-Nicholas and COA. The optimal control approaches as LQR and OPS have the characteristic of steady-state error. Moreover, they require the access for full state variables. This limits their applicability. Whereas, Ziegler-Nicholas PI and PID controllers have relatively long settling time and high overshoot. The controllers tuned via COA remedy the defects of optimal and zero steady-state controllers. The performance adequacy of the proposed controllers is assessed for different operating scenarios. Matlab and its dynamic platform, Simulink, are used for stimulating the system under concern and the investigated control techniques. The simulation results revealed that COA results in the smallest settling time and overshoot compared with traditional controllers and zero steady-state error controllers. In the overshoot, COA produces around 80% less than LQR and 98.5% less than OPS, while in the settling time, COA produces around 81% less than LQR and 95% less than OPS. Moreover, COA produces the lowest steady-state frequency error. For Ziegler-Nicholas controllers, COA produces around 53% less in the overshoot and 42% less in the settling time.

Keywords: Chaos, Linear Quadratic Regulator, Optimal Pole Shifting, Single-Area Power System, Load Frequency Control, Eigenvalues

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I. INTRODUCTION

LFC received more attention over the past decades, as it is fundamental for proper operation of the modern power system. The large frequency deviations are reported to cause enormous problems for different components of the power system: generation, transmission and loads [1-3]. LFC maintains the generated and tie-line powers within the prescribed levels during and post disturbance, which could retain the frequency and restore the stability [3-5].

Different control methodologies are reported in the literature for realizing LFC [1-17]. Optimal control approaches as LQR, OPS and H_∞ are applied for LFC problem. These methods are characterized by fast response [6-8]. However, a steady-state frequency error is unavoidable in these techniques. Moreover, they require full access for different system states [6-8].

PI and PID controllers successfully eliminate steady-state frequency error forcing the frequency deviation to zero following severe disturbance [9-11]. Different approaches are advised for tuning the parameters of PI and PID controllers. However, Ziegler-Nicholas empirical approaches, the process reaction and the continuous cycling methods, proved to be efficient, simple and robust techniques for tuning PI and PID controllers. In general, the empirical approaches suffer from inadequate design that could result in sluggish or prolonged response [9-12].

Recently, meta-Heuristic optimization techniques are applied for different areas in the power system control and operation. They converge to optimal solution swiftly, without prior knowledge for the problem under concern. This reduces the computation requirements while boosts robustness of the developed solutions. Different evolution algorithms are reported for the problem of LFC. However, they differ according to the hyperspace search mechanism. Some are initial solution dependent, while other modify and direct the search according to their probabilistic rules [13-17].

Chaos generally is a bounded unstable dynamic behavior of the nonlinear systems. It depends on the initial conditions and includes infinite unstable periodic motions. Chaotic systems have a salient feature that a slight change in parameters and or initial conditions results in widely different future behavior, as periodic oscillations, bifurcations, and ergodicity. This characteristic is not only restricted on complex systems but even reported in the simplest ones, as logistic equation. This is attributed to the nonlinear interaction between the elements within the system. The application of the chaotic sequences could be an interesting alternative to provide the search diversity in an optimization algorithm. Due to the non-repetitive natureof the chaos, it could carry out the overall search at higher speeds than the meta-heuristic methods which depend on the probabilities [18-24].

COA, a global optimization algorithm, was developed and implemented for different engineering problems. It is emerged based on chaos behavior of nonlinear systems. COA is a robust optimization approach that enjoys the irregularity and stochastic properties of the chaos. It uses the numerical sequences that generated by the chaotic maps. COA is a global search algorithm that escapes local solutions by searching the irregularity of the chaotic motion. Moreover, it has the advantages of reliability, ergodicity and stochastic features [20-26].

LFC of single-area is extensively investigated in the literature. Different control methods as mentioned are being advised including evolutionary algorithms. However, a little is reported about COA for LFC problem. COA could remedy the deficiency of traditional, optimal and evolutionary algorithms. In this work, the LFC of single-area power system model is used as pilot example for expressing the adequacy of meta-heuristic techniques in designing optimal controller compared with the reported optimal methods as LQR and optimal pole shift.

In this article, a thoroughly comparison between COA and different control approaches are advised for tuning the parameters of LFC. The optimal control approaches as LQR and OPS result in steady-state frequency error. They are similar to Proportional (P) controller. Therefore, the comparison is extended to the controllers that eliminate the frequency steady-state zero error. These are PI and PID control methods. The article also introduces a comparison between COA and Ziegler-Nicholas tuning methods for PI and PID controllers. The visibility of COA is authenticated via testing the different controllers for significant abrupt change in the load power of steam power plant. Matlab and its dynamic platform, Siumlink, are used to stimulate the system under concern and code the different control techniques. Therefore, this article could claim to have the follow contributions:

- Introducing comprehensive review for different approaches advised for LFC,
- Introducing thoroughly discussions for COA and its mapping method and objective function.
- Advising simple and robust COA for tuning different types of controllers used for LFC, such as: P, PI and PID.

II. STEAM POWER SYSTEM

The block diagram for the steam power plant load frequency control is given in Fig.1. The parameters of steam power plant under concern are given in the appendix. The state-space model of LFC for this system is given by [1,3,5],

$$\begin{bmatrix} \Delta\dot{f} \\ \Delta\dot{P}_g \\ \Delta\dot{X}_g \end{bmatrix} = \begin{bmatrix} -\frac{1}{t_p} & \frac{k_p}{t_p} & 0 \\ 0 & -\frac{1}{t_t} & \frac{1}{t_t} \\ -\frac{1}{Rt_g} & 0 & -\frac{1}{t_g} \end{bmatrix} \begin{bmatrix} \Delta f \\ \Delta P_g \\ \Delta X_g \end{bmatrix} + \begin{bmatrix} -\frac{k_p}{t_p} & 0 \\ 0 & 0 \\ 0 & \frac{1}{t_g} \end{bmatrix} \begin{bmatrix} \Delta P_d \\ \Delta P_{tie} \end{bmatrix} \quad (1)$$

where ΔP_g, ΔP_d and Δf are deviation of generator delivered power, demand frequency independent power and output frequency respectively. k_p is the turbine-generator gain. t_g and t_t, t_p are governor, prime mover and generator time constants respectively. ΔP_{tie} is the tie-line power deviation. R is the load-frequency droop gain. ΔX_g is the signal applied to the turbine.

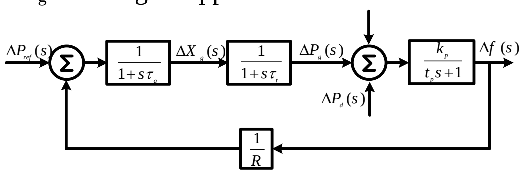

Fig. 1. LFC of single-area power system without control

where ΔP_{ref} is the power reference signal. s is the Laplace operator. Fig. 1 illustrates the model of one-stage thermal turbine power system without control.

III. OPTIMAL CONTROL TECHNIQUES

Two control methods are used to validate the proposed COA. These are linear quadratic regulator and optimal pole shifting. These methods are considered from optimal control methods.*III.1 Linear Quadratic Regulator*

LQR yields robust optimal controller for a system expressed in the state-space form [7],

$$\dot{x} = Ax + Bu \quad (2)$$

where x is the state vector; A is the state matrix; B is the control matrix and u is the control vector. $\dot{x}$ is the derivative vector of the states. The optimal controller based on LQR is given by [12],

$$u_{opt} = -k_{opt} x \text{ where } k_{opt} = R^{-1} B^T P \quad (3)$$

where u_{opt} is the optimal control; k_{opt} is the gain of the optimal control. R is the control weight matrix. P is the Riccati matrix.

This optimal control u_{opt} is designed to minimize the quadratic performance index [12],

$$J = \int_{t_0}^{t_1} \left(x^T Q x + u_{opt}^T R u_{opt} \right) dt \qquad (4)$$

where Q is the state weighting matrix. P, the Riccati matrix could be obtained by solving matrix Riccati equation [12].

$$PA + A^T P + Q - PBR^{-1}B^T P = 0 \quad (5)$$

III.2 Optimal Pole Shifting

Optimal pole shifting is used for relocating the poles in order to increase the stability margin and/or reduce the overshoot and settling time. Its principle is comprehensively reported in the literature [6-8]. A brief review is given in the following.

The optimal pole shifting technique for several poles is implemented individually for each real pole or a pair of complex poles. Then, the matrix of the controller gain k_{opt} for relocating the system poles is the summation of the optimal feedback matrix for each pole as given by,

$$k_{opt} = \sum_i k_i \qquad (6)$$

where k_{opt} is the controller gain for allocating the required system poles optimally. k_i is the controller gain for placing i pole in optimal pattern [12].

$$k_i = PR^{-1}G^T C^T \qquad (7)$$

where C^T is the left eigenvector associated with eigenvalue $\lambda=\gamma$ of the open loop poles of state matrix A for real pole . C^T for imaginary pole is $C^T = \left[C_1^T \quad C_2^T \right]^T$, which is the left eigenvectors associated with the complex pole. where G and P are given by [12],

$$P = V^{-1}, \quad G = C^T B \qquad (8)$$

The matrix V is obtained for real pole by solving first order Lyapunov equation[12],

$$(\alpha + \sigma)V + V(\alpha + \sigma) = H \qquad (9)$$

In case of complex pole, the matrix V is obtained by solving second order Lyapunov equation [12],

$$(F + \sigma I)V + V(F^T + \sigma I) = H \qquad (10)$$

IV. CHAOS OPTIMIZATION ALGORTHIM

The procedure for implementing COA in this search is highlighted in the following[18-22]:-

- A chaotic sequences generator is defined based on a chaotic mapping method. This generator generates the search point in the research hyperspace.
- The objective function is evaluated for each design point.
- Current solution is the point with minimum objective function. The migration of current position into global optimum is accomplished through chaotic process.
- Repeat the previous step until convergence condition is fulfilled; then the global optimum is reached.

Different chaotic mapping approaches are reported such as He'non, Zeraoulia and Lozi [19-26]. However, the Lozi map is considered to be the most preferred option, as it is simple and maps the search hyperspace more efficient.

The Lozi map is a simple discrete two-dimensional chaotic map. The design points could be generated via Lozi map by [19],

$$x_c(k+1) = 1 - a\left|x_c(k)\right| - by_c(k) \qquad (11)$$

$$y_c(k+1) = x_c(k) \qquad (12)$$

where x_c and y_c are the coordinates of lozi map; k is iteration number. Typical values of the constants a and b are 1.7 and 0.5 [19] respectively .

Fig. 2 shows how Lozi map maps the search hyperspace. Lozi map, Fig. 2, depicts the prosperities of the chaos as non-repetition, stochasticity and ergodicity. It maps the hyperspace more efficient than other optimization methods that depend on probability. As, the moving from one point to another is a chaotic process as given by equations (11) and (12).

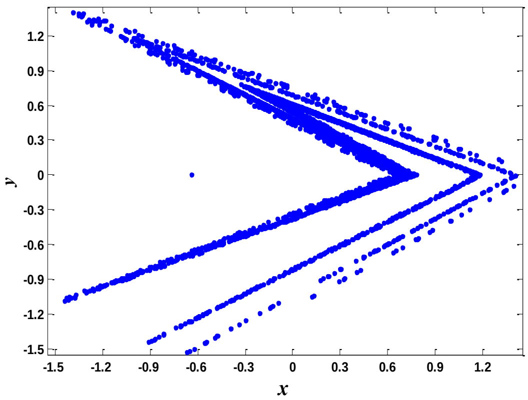

Fig. 2. x_c versus y_c of chaotic Lozi map

The variable $y_c(k)$ is normalized in the range [0;1] to each decision variable in the n-dimensional search hyperspace using the transformation [19-26],

$$z(k) = \frac{y(k)-\alpha}{\beta-\alpha} \tag{13}$$

where [α,β]=[-0.6418,0.6716]. The current solution $x_i(k)$ could be expressed in terms of best local solution $\bar{X}_i$ and step size λ in chaotic local research as [22,23],

$$x_i(k)=\begin{cases} \bar{x}_i+\lambda z_i(k)\left|U_i-L_i\right| & r \le 0.5 \\ \bar{x}_i-\lambda z_i(k)\left|U_i-L_i\right| & r \ge 0.5 \end{cases} \tag{14}$$

where L_i and U_i are the lower and the upper limits. The flow chart of COA based on Lozi map is shown in Fig. 3. M_g and M_l in Fig. 3 are maximum number of iterations of chaotic global and local research respectively.

Design criteria of the proposed COA technique is to identify optimal parameters of the controller k_{opt} that damp efficiently and promptly the oscillations either in generated power, mechanical power and frequency following a small or severe disturbance. Moreover, the advised controller forces the operating point to track efficiently the set point with minimum settling time following large/small abrupt change in the command.

The proposed objective function considers minimizing the integral time of the absolute error of the frequency as given by (15).

$$Of = \int_0^{t_{sim}} t\left(\left|\Delta f\right|\right)dt \tag{15}$$

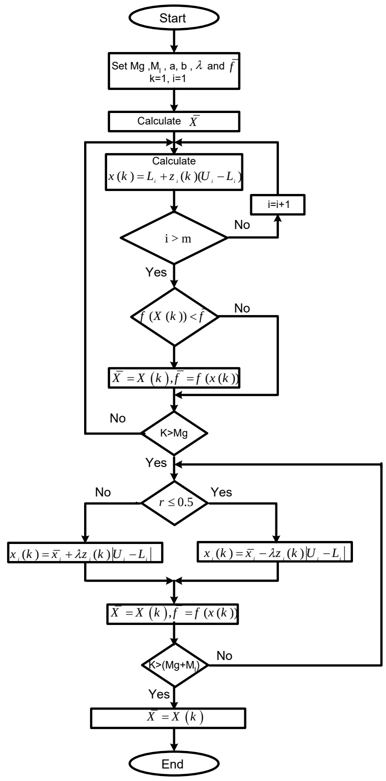

Fig. 3. CH algorithm flow chart

where *Of* is the objective function and t_{sim} is the time range of the simulation. Thus for calculating the objective function, the time-domain simulation of power system model under concern has to be carried out over the simulation period ($0\text{-}t_{sim}$). The objective function, (15), minimizes the deviation in the frequency, as under different disturbances\load levels the efficient controller has to maintain stability and hence synchronism. The objective function *Of* given in equation (15) has the advantages of :

- Ease of implementation due to the ease of accessibility of the input signal.
- Simplicity, only single input signal.
- Reduced computation requirements in terms of storage and speed.
- Effectiveness and robustness.

V. RESULTS AND DISCUSSIONS

The frequency deviation for 20% step increase in the system mechanical power is illustrated in Figs. 4-8 for LQR, OPS ,COA and zero steady-state control methods. This is to assess the functionality and applicability of the proposed COA for optimizing the performance of steam power system regarding the fluctuation in the line frequency.

V.1COA versus OPS and LQR

The step response for a 20% increase in the load power is given in Fig. 4 for the system under concern under different control techniques.

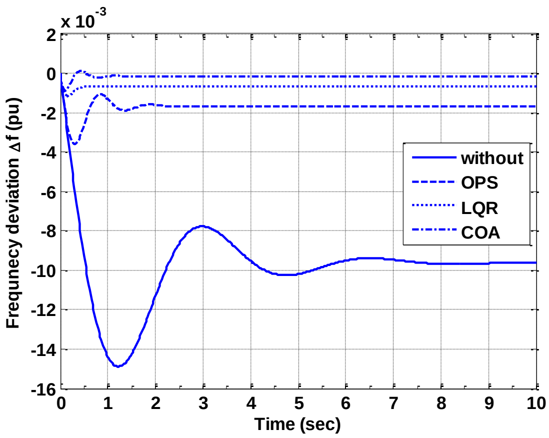

Fig. 4. Step response for 20% increase in the load power for without (solid), OPS(dashed), LQR (dotted) and COA(dashed-dotted)

Fig. 4 confirms the superiority of COA, as it produces the lowest steady-state frequency deviation. Moreover, it has relatively short settling time. COA converges to optimal solution better than LQR. This is attributed to hyperspace search mechanism of COA, as shown in Lozi map, Fig. 2.

The open and closed loop poles of steam power plant without/with LFC tuned by OPS, LQR and COA are given in Table 1. The parameters of the controller obtained from OPS, LQR and COA are given in Table 1.

Table 1: Open and closed loop poles of steam power plant for OPS, LQR and COA

Poles	without	OPS	LQR	COA
	-5.89 -0.6+1.78i - 0.6-1.78i	-15.0 -2.8+1.78i -2.8- 1.78i	-39.8 +39.68i -39.8 - 39.68i -2.0	-125.77 + 125.72i -125.77 – 125.72i -2.00

In COA and LQR, the location of the poles are changed. Moreover, the real pole in COA and LQR is moved close to imaginary axis compared with OPS. However, COA and LQR produced the best performance in terms of overshoot and settling time. This is shown in Fig. 5 and also in Table 2.The response indicators, overshoot and settling time, for the system under concern without control and from OPS, LQR and COA for 20% increase in the load are given in Table 2.

Table 2: Overshoot (OS) and Settling Time (ST) for the steam power plant without control, OPS, LQR and COA

	without	OPS	LQR	COA
OS(%)	55.2	32.5	2.5	0.5
ST(sec)	6.62	3.92	0.92	0.18

The root locus of the poles for the system under concern without control and from OPS, LQR and COA are shown in Fig. 5.

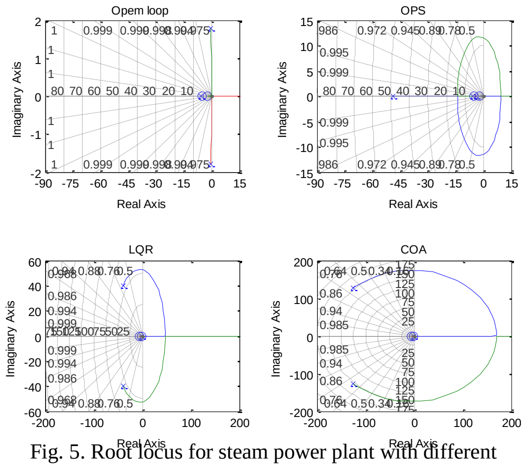

Fig. 5. Root locus for steam power plant with different controller

Fig. 5 shows that OPS provides better stability margin than LQR and COA. In general, the system with control is stable, Fig. 5. COA produces better stability limit than LQR. This is shown in Table 2 and Fig. 5. Moreover, COA has the best performance regarding settling time and overshoot. The parameters of the controller obtained from OPS, LQR and COA are given in Table 3.

Table 3: Parameters of the controller from different approaches

Method	Parameters of the controller K $[K_1 \quad K_2 \quad K_3]$
OPS	[5.45 10.3 -39.2]
LQR	[6.6 1.96 -114.2]
COA	[8.4 50.2 -150.4]

V.2 COA versus Ziegler-Nicholas for PI control

Fig. 4 shows that optimal control approaches suffer from nonzero steady-state error. The optimal control approaches could be considered as proportional controller. To eliminate the steady-state frequency error, PI and/or PID controllers are implemented. Different approaches are used for tuning the parameters of PI/PID controllers. Some approaches require sophisticated modelling for the system. Ziegler-Nicholas approach is simple and empirical tuning method for PI/PID controllers. Ziegler-Nicholas has two schemes: process reaction and cycling method techniques. The system under concern equipped with PI/PID controllers is shown in Fig.6.

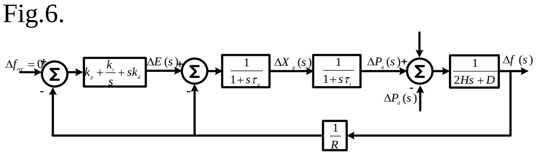

Fig. 6. LFC of single-area power system with PI/PID control

Usually Automatic Generation Control (AGC) employs an integral controller, such that the frequency deviation converges to zero as the disturbance diminishes. However, the integral control could result in excessive overshoot and prolonged settling time. Therefore, AGC is modified into PI or PID controllers as shown in Fig. 6.

The step response of LFC with PI controller tuned via COA and the continuous cycling method of Ziegler-Nicholas for a 20% abrupt increase in the load power is given in Fig. 7.

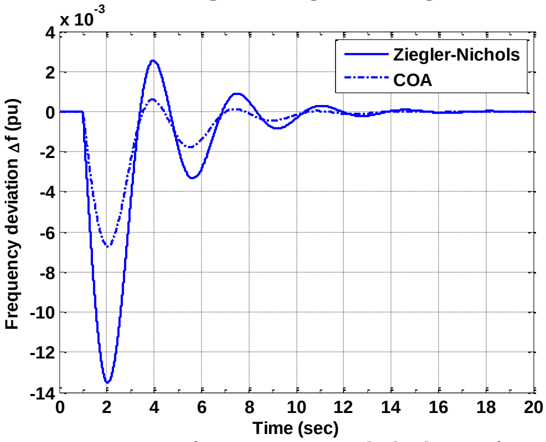

Fig. 7. Step response for 20% increase in the load power for PI controller via continuous cycling Ziegler-Nichols (solid), COA(dashed-dotted)

It is obvious from Fig. 7 that COA is more efficient in tuning PI controller than the empirical method. The COA produces 53% less in the overshoot than Ziegler-Nicholas method. Moreover, the settling time of COA is around 42% less than cycling approach. The parameters of PI controller from COA and continuous cycling techniques are given in Table 4

Table 4: Parameters of the controller from Ziegler-Nichols and COA

Method	**Parameters of the controller**	
	kp	**ki**
Continuous cycling Ziegler-Nichols	24.5	15.1
COA	18	9.8

V.3COA versus Ziegler-Nicholas for PID control

The step response of LFC with PID controller tuned via COA and the continuous cycling method of Ziegler-Nicholas for a 20% abrupt increase in the load power is given in Fig. 8.

Comparing Figs. 7 and 8 indicates that PID controller has better performance than PI regarding the percentage overshoot and settling time. COA again proves its superiority for dimensioning the PID controller. PID based COA has less overshoot and settling time than Ziegler-Nicholas counterpart. It produces around 90% and 50% reduction in the overshoot and settling time.

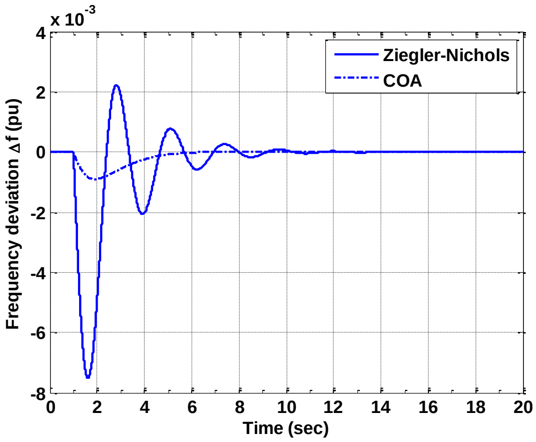

Fig. 8. Step response for 20% increase in the load power for PID controller via continuous cycling Ziegler-Nichols (solid), COA(dashed-dotted)

The parameters of PID controller tuned via COA and the continuous cycling methods are given in Table 5.

Table 5: Parameters of the controller from Ziegler-Nichols and COA

Method	**Parameters of the controller**		
	kp	**ki**	**kd**
Continuous cycling Ziegler-Nichols	30	30.92	7.3
COA	2	10.54	10.4

VI. CONCLUSION

A robust and reliable chaotic optimization algorithm is advised in this work to determine the optimal parameters of AGC. The proposed approach is validated against different controllers for different operating scenarios. The COA results in smaller settling time and the steady-state frequency error than LQR and OPS. In the overshoot, COA produces around 80% less than LQR and 98.5% less than OPS, while in the settling time, COA produces around 81% less than LQR and 95% less than OPS. COA is also compared against PI and PID controller tuned via Ziegler-Nichols method. Again, COA produces better response in terms of settling time and overshoot. For PI, COA produces around 53% less in the overshoot and 42% less in the settling time. For PID, COA produces around 90% and 50% more reduction in the overshoot and settling time than the conventional PID.

It could be concluded that COA is a better option for designing the LFC controller than optimal and intelligent control approaches. Detailed mathematical representation for the controlled system is not required in COA. Moreover, COA could be directed to satisfy conflicting requirements, which may be not achievable in some control methods.

APPENDIX

The parameters of the steam power plant under concern are given in Table 6.

Table 6: Parameters of steam power plant

Turbine time constant T_t	0.5sec
Governor time constant T_g	0.2sec
Speed droop gain R	0.05pu
Gain k_p	1.25
Time constant T_p	10.25sec

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