Load frequency control of interconnected power system using cuckoo search algorithm

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Article Info

Article history:

Received May 12, 2023
Revised Sep 30, 2023
Accepted Oct 12, 2023

Keywords:

Cuckoo search optimization
Load frequency control
Proportional integral derivative controller
Time domain specification
Two area control system

ABSTRACT

This paper presents a new time-domain multi-objective function approach for solving load frequency control issue in an interconnected power system. The performance of interconnected power system in each area is validated for overshoot and settling time values of frequency change and tie-line power exchange. An objective function is created with the goal of enhancing proportional integral derivative (PID) controller settings by reducing overshoot and achieving faster time-domain settling times. The efficiency of the proposed time-domain multi-objective function is evaluated in a two-area thermal power plant using a nature-inspired cuckoo search optimization (CSA) technique. By comparing the time-domain simulation results of the test system with the existing integral error-based objective functions IAE, ISE, ITAE, and ITSE, the proposed objective function is validated. Further, a sensitivity analysis were carried out to analyze the robustness of the proposed multi-objective function under various uncertain conditions.

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1. INTRODUCTION

Electrical power system reliability and stability is a continuous state of interest owing to the uncertainty of loads. These uncertainties lead to rapid change in power demands, which in turn deviates the system frequency and tie-line power values deviate from their predetermined levels. A significant frequency deviation may lead to voltage collapse in the system. Therefore, it is essential to control the frequency deviation within the predefined values throughout the operation [1]. Load frequency control (LFC) is critical for large-scale power system stability and reliability. Its primary objective is to keep frequency and power flow within reasonable ranges. This successfully regulates load changes and system disturbances. LFC controls power generation and frequency to keep voltage within specified ranges. It ensures adequate power quality for the proper operation of electrical devices. In conclusion, LFC is a critical mechanism for the smooth operation of large-scale power networks. When the system is subjected to a disturbance, the controller mechanism seeks to reduce the transitory behaviour of the system response.

LFC functions as an auxiliary controller, reducing the number of oscillations in frequency deviation and tie-line power exchanges for load perturbations. This procedure contributes to the system's seamless and secure operation [2], [3]. Several research works and novel strategies have been used to the subject of LFC throughout the last few decades. The use of linear controllers in power networks presents issues due to the system's intrinsic nonlinearity, which affects accuracy and efficiency. To solve this, nonlinear controllers provide increased precision and efficiency at the expense of intensive computations and exact mathematical models. As a result, response time and design complexity both rises. In the design of LFC systems, achieving a balance between controller performance and computational needs becomes critical. Researchers and engineers are always working to create appropriate control solutions for managing nonlinearity in power systems while preserving operational efficiency and dependability [4]. Various control systems have been used to LFC, including robust control, decentralized control, linear quadratic problem, pole placement approach, variable structure control, and state feedback, but each has drawbacks that restrict their usefulness [5]. Robust control can be computationally demanding and necessitates precise modeling. Decentralized control has difficulties with zone coordination and communication delays. The LQR method is based on exact system parameter information. Pole positioning may be unstable. State feedback necessitates full-state information, which can be difficult to get in large-scale systems. Obtaining balance between control performance, simplicity, and robustness remains a problem, and hybrid control solutions are being intensively researched to improve LFC efficiency and reliability in complex power systems. While these techniques are effective in handling the nonlinear aspects of the power system, they still have their own issues.

Evolutionary algorithm (EA) techniques offer an effective approach to address the LFC problem by efficiently handling nonlinear objective functions. Among this techniques, cuckoo search algorithm (CSA) [6]–[11], fractional order proportional integral derivative (PID) controller based on gases brownian motion optimization (GBMO) [12], [13], hybrid grey wolf optimization and CSA [14], [15], novel hybrid local unimodal sampling (LUS) and teaching learning based optimization (TLBO) based fuzzy-PID controller [16], CSA and particle swarm optimization (PSO) [17], artificial bee colony (ABC) algorithm [18], PID controller coordinated with redox flow batteries (RFBs) [19], hybrid bacteria foraging optimization algorithm and particle swarm optimization [20], observer-based sliding mode control [21], grey wolf optimizer algorithm [22], firefly algorithm [23], quasi-oppositional grey wolf optimization algorithm [24], squirrel search optimization and recurrent neural network [25], fuzzy-based PID droop controller [26], archimedes optimization algorithm [27], CSAbased for tunning both PI and fractional order proportional integral derivative (FOPID) controllers [28], modified fletcher-reeves method [29], PSO and CSA [30], artificial CSA [31], cuckoo search (CS) and neural network [32], have gained popularity in the design of LFC controllers.

EA approaches are utilized in LFC due to their effectiveness in handling nonlinear objective functions. However, caution is necessary since adjusting the controller settings becomes an optimization problem, with the integral term as the objective function and controller parameters as decision parameters. IAE and ISE criteria's equal weighting of errors causes delayed error propagation. To improve this, ITSE and ITAE criteria introduced time as a multiplier to the error term, resulting in decreased settling time and improved responsiveness. Many researchers mainly focussed on developing a robust and straightforward controller for LFC to ensure system stability and robustness against varying parameters. To achieve this, various evolutionary optimization techniques were considered. The integral error functions commonly used in LFC aim to minimize absolute and square error values. However, these functions do not directly address the minimization of transient response parameters simultaneously. To overcome this limitation, a new objective function was proposed, incorporating transient response parameters as optimizing variables.

This paper presents a novel optimization algorithm, CS, for tuning the parameters of a proportional integral (PI) controller in the load frequency control (LFC) problem [33]–[35]. The primary aim of this research is to demonstrate and validate the robustness of the CS-based PI controller. Additionally, the study seeks to enhance the performance of frequency deviation and tie line power under different loading conditions, considering the presence of system nonlinearities. By utilizing the CS algorithm, the proposed controller is expected to optimize LFC performance, ensuring stability and improved response in power systems with varying loads and nonlinear characteristics. The findings from this study contribute to advancing control strategies for LFC, efficient and reliable power system operation. Section 1: introduction, which provides an overview of works done in last decades. Section 2: problem formulation, system modelling, outlining the LFC issue linked in power systems. Section 3: implementation of the CS algorithm, including a flowchart to solve the LFC issue. Section 4: test results and comparative analysis evaluates the proposed CS-based approach and compares it to existing control systems. Section 5: conclusion of work.

2. SYSTEM DESIGN

The dynamic load model of the LFC was explored in this section. Figure 1 shows the detailed transfer function model of two area thermal power systems whose dynamic response is studied. Nominal values of system parameters are tabulated in Table 1. In Figure 1, R_i represent the speed regulation of governor, β_i is frequency bias constant, T_{Gi}, T_{ti}, T_{Pi} are time constant of governor, turbine, and generator,

K_{Gi}, K_{ti}, K_{Pi} are gain constants of governor, turbine, and generator, ΔP_{D1}, ΔP_{D2} steps incremental change at area-1, area-2, Δf_1, Δf_2 are frequency deviation at area-1 and area-2, ΔP_{12} is tie-line power exchange between area-1 and area-2 and area control error (ACE_i) of respective areas and U_i are control input at respective areas. The transfer functions of the various blocks utilized in the power system model are shown below. Transfer function of the governor is $\frac{K_{G1}}{1+ST_{G1}}$, transfer function of the turbine is $\frac{K_{T1}}{1+ST_{T1}}$, transfer function of the generator is $\frac{K_{P1}}{1+ST_{P1}}$. For the ith area, the AEC signal made by frequency and tie line power variations is represented as: $ACE_i = \beta_i \Delta f_i + \Delta P_{tie\ i}$. The usual ranges of the gains are taken as [-2 to 2] and objective function evaluated under load disturbance of 1% in all areas [36]. LFC has classified into two operation modes based on the system's control signal. They are uncontrolled case: when control signal (U_1, U_2) values are zero. Controlled case: when control signal (U_1, U_2) values are non-zero. The system under investigation was studied for controlled cases. PID controller input is ACE, and output is U_i. ACE_i treated as load frequency controller output which gives a degree of balance between generation, and load demand where U_i is controlled input to the plant is given by (1) and (2):

$$ACE_1 = \beta_1 \Delta f_1 + \Delta P_{12}, ACE_2 = \beta_2 \Delta f_2 - \Delta P_{12} \quad (1)$$

$$U_1 = K_{P1} ACE_1 + K_{i1} \int ACE_1 + K_{D1} \frac{d}{dt} ACE_1, U_2 = K_{P2} ACE_2 + K_{i2} \int ACE_2 + K_{D2} \frac{d}{dt} ACE_2 \quad (2)$$

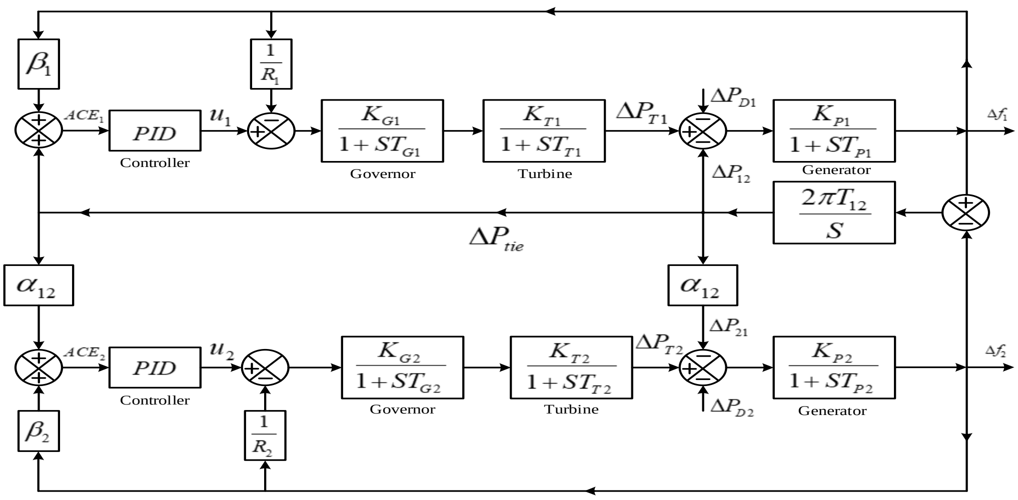

Figure 1. Transfer function model of two areas interconnected power system

Table 1. Cuckoo and PSO search variable

Parameter	Value	Parameter	Value	Parameter	Value
Number of nests	25	Search domain	3	Population in swarm	60
Number of trials	50	K_P, K_I, K_D	[0: 2.5]	C1=C2	2.5
Max generation	100	ρ_a	0.25	ω	1.0

3. METHOD

3.1. System evaluation criteria

When the system is subjected to a disturbance or input, the performance of the control system is evaluated. Before reaching the steady-state value, the system typically exhibits transitory response oscillations. Transient response is defined by two factors: how quickly the system responds to the input or disturbance connecting time-domain parameters; i) how stable the system is and ii) how near is the system response to the planned output connecting time-domain parameters maximum peak overshoot and settling time. The system's desired performance is defined by time-domain parameters such as maximum peak overshoot (mp), rising time (tr), settling time (ts), and steady-state error (Ess). The controller design goal is to minimise the time-domain characteristics. The error signal is defined by the step input U(t) and the system response y(t) which is expressed in (3) as:

$$e(t) = U(t) - y(t) \quad (3)$$

3.1.1. Performance indices

Fitness functions can be used to optimise control system design for i) time-domain response parameters and ii) integral error of full-time response. Four performance indices have been commonly utilised in the literature to prove the superiority of the developed controller, such as IAE, ISE, ITAE, and ITSE. In (4) gives these performance indices:

$$IAE = \int_0^{tfinal} |e(t)|\, dt;\ ISE = \int_0^{tfinal} e(t)^2 dt;\ ITSE = \int_0^{tfinal} t\,|e(t)|\, dt;\ ITAE = \int_0^{tfinal} te(t)^2 dt \quad (4)$$

Where $tfinal$ is the time taken by the system to reach a steady state. The study reveals that lower values of the specified indices are associated with superior system response in the time domain. As these indices decrease, the power system model exhibits improved transient behavior and faster settling times, signifying enhanced performance. The ISE and IAE functions are independent of time and offer equal weight to all errors. Optimizing control system using ISE and IAE response results in relatively smaller overshoot but extended settling time. To overcome this issue, ITSE and ITAE use a time multiplier for weighing the errors and highlights the long duration errors. Consequently, response resulted in lesser settling time using ITAE and ITSE. Eventually, these functions attempt to minimize the absolute and squared error signals, respectively. However, this does not mean minimizing transient response parameters M_P, t_s, t_r, and E_{ss} at the same time. Therefore, the weighted sum of time parameter's objective function has been proposed to improve the PID response, as represented in the expression (5) as:

$$F = \left(1 - e^{-\beta}\right)\left(M_p + E_{ss}\right) + e^{-\beta}\left(t_s - t_r\right) \quad (5)$$

Where β is a weight factor that lets the designer to choose between fastness and closeness of response w.r.t. desired response. To minimise the M_P and E_{ss}, β should be choosen a value more than 0.69, and to minimise the t_s and t_r, β should be choosen a value less than 0.69. The proposed objective function in this research evaluates fitness value to a minimum by taking=0.69. Following the controller architecture, optimise the restricted PID gains listed in (6):

$$K_P^{min} \le K_{P\ optimum} \le K_P^{max},\ K_I^{min} \le K_{I\ optimum} \le K_I^{max},\ K_D^{min} \le K_{D\ optimum} \le K_D^{max} \quad (6)$$

3.2. Cuckoo search optimization

CS is a metaheuristic algorithm that has been proposed by Yang and Deb in 2010 [37]. These algorithms use a pattern search that relates to random solutions to the problem. Here in the CS, the pattern corresponds to an artificial nest. Cuckoo follows an aggressive reproduction strategy i.e egg-laying and breeding of cuckoo forms the basis for the algorithm. The flowchart for CSA is shown in Figure 2.

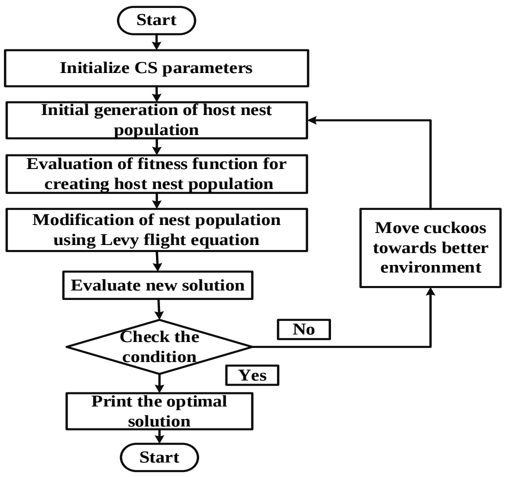

Figure 2. Flowchart of CS optimization algorithm

CS is based on three prominent rules; i) the cuckoo lays an egg and dumps its egg in random nests and ii) best nest of high quality carried to the next generation.

No. of available nests are fixed, and egg laid by cuckoo is discovered by host bird with probability (ρ_a) ε [0,1]. If the host detects the cuckoo egg, either it may throw or leave the cuckoo egg. Rule 3 is approximated by probability factor (ρ_a) and n nests are replaced with new nests. While generating new solution X_i^{t+1} for i^{th} cuckoo, a levy flight is carried out by (7):

$$X_i^{t+1}=X_i^t+\alpha * Levy(\lambda) \quad (7)$$

Where α>0 is the step size. Levy flight supply random walk close to the best solution, which accelerates the local search. Adequate far-field random solutions are generated from the best solution so that the system does not come in a trap of local optimum. In Table 1, CS parameters are given.

4. RESULTS AND DISCUSSION

The main objective of the simulation study is to test the applicability and effectiveness of the proposed time-domain objective function using a CS optimization algorithm to solve the LFC problem. The objective function was implemented in two areas thermal power system, and transient performance were evaluated under normal and disturbed conditions. The transfer function modelling of the test system shown in Figure 1 have been executed in the Simulink platform and optimization algorithm code written in MATLAB. The nature of the optimization algorithm owns random initialization. Different independent trails are carried to extract best result.

4.1. Area-1 subjected to 1% SLP

The secondary control (SC) signal for the test system is obtained from the PID controller. In this case, SC signal gains are optimized concurrently using the CSO technique with a 1% step load perturbation (SLP) at area-1. Attained optimal controller gains values by CSO are tabulated in Table 2 for considered objective functions. The obtained % peak overshoot and settling time value of these responses have been tabulated in Table 3. Integral gain accelerates the response towards set-point and eliminates the residual error present in the response. Since integral gain deals with the accumulated past errors, too much of integral gain can lead present value to overshoot. Derivative gain estimates the behaviour of the system and improves the settling time and stability. To rank the objective functions in terms of system oscillatory behavior, the descending order is as follows: ISE, ITSE, ITAE, IAE, and the proposed function. These rankings provide valuable insights into the trade-offs between different objective functions for control system design. While ISE may lead to a more oscillatory response, the newly proposed function stands out as a promising choice for minimizing integral gain and enhancing overall system performance. From Table 2, it is observed that obtained the integral gain value associated with CSO is 1.01, smallest value compared to all other objective functions at area-1 with PSO algorithm (1.24). While considering, derivative gain value of objective functions, ISE has the least value 0.72 due to which the response of the system is more oscillatory.

Table 2. Optimized controller gains with 1% SLP at area-1

	Area-1			Area-2				Area-1			Area-2		
Case	Kp1	Ki1	Kd1	Kp2	Ki2	Kd2	Case	Kp1	Ki1	Kd1	Kp2	Ki2	Kd2
PSO	1.42	1.24	1.39	1.65	1.28	1.15	CSO	1.20	1.01	1.26	1.33	1.14	1.04
IAE	0.97	2.10	2.24	1.71	1.57	0.97	IAE	0.88	1.99	1.98	1.58	1.44	1.06
ISE	0.75	2.25	0.85	1.21	1.98	1.18	ISE	0.61	2.00	0.72	0.96	1.78	1.05
ITAE	0.84	2.20	2.19	1.32	2.18	2.01	ITAE	0.69	2.00	2.00	1.15	2.00	1.92
ITSE	0.69	2.15	1.54	1.64	1.51	1.14	ITSE	0.53	2.00	1.35	1.46	1.39	1.05

Table 3. Overshoot and settling time with 1% SLP

	% Peak overshoot			Settling time (secs)				% Peak overshoot			Settling time (secs)		
Case	ΔF1	ΔF2	ΔP12	ΔF1	ΔF2	ΔP12	Case	ΔF1	ΔF2	ΔP12	ΔF1	ΔF2	ΔP12
PSO	1.52	0.48	1.96	6.10	3.01	3.10	CSO	1.32	0.36	1.77	5.65	2.5	2.55
IAE	1.62	1.08	1.87	7.98	3.45	2.65	IAE	1.54	0.97	1.78	7.23	3.15	2.23
ISE	2.01	1.12	2.14	11.10	6.12	2.45	ISE	1.85	0.99	1.97	10.1	5.82	1.98
ITAE	1.78	1.66	1.72	8.10	3.80	2.98	ITAE	1.58	1.46	1.57	7.95	3.23	2.40
ITSE	1.98	1.25	2.14	9.56	3.01	2.55	ITSE	1.75	1.04	1.96	9.08	2.65	2.15

Consequently, the proposed CS approach offers enhanced accuracy and faster response times, making it a more efficient choice for complex dynamical systems. The oscillatory behaviour of the system shows a significant effect on the settling time. From Table 3, it is observed that the obtained result with CSO for proposed function has the least settling time, and ISE has the highest settling time. The behaviour of the system at area-1 with all other objective functions is represented in Figure 3. Even though perturbation is applied at area-1, there will be minor frequency variations at area-2 due to tie-line power exchange between both areas. It is noted that the proposed function with CSO has minimum integral and derivative gain values even at area-2, which leads to minimum overshoot and settling time compared to other objective functions as shown in Figure 4. The overshoot values of frequency change at area-2 from Table 3 in descending order then ITAE followed by ITSE, ISE, IAE, and proposed function. Figure 5 represents the obtained changes in frequency with 1% SLP applied at area-1 and area-2. Therefore, it is predominantly observed that proposed function is less sensitive to the frequency change at area-2 and tie-line power exchange compared to other objective functions with 1% SLP is represented in Figure 6.

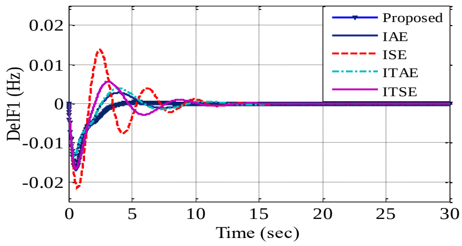

Figure 3. Change in frequency at area 1 with 1% SLP

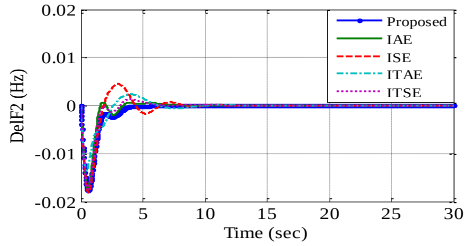

Figure 4. Change in frequency at area 2 with 1% SLP

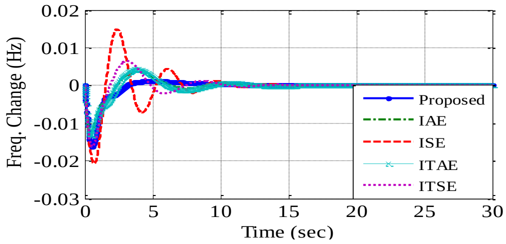

Figure 5. Change in frequency with 1% SLP in both areas

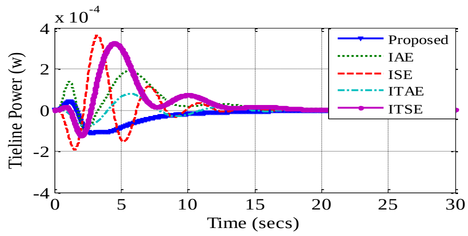

Figure 6. Change in tie-line power exchange with 1% SLP

4.2. Both area-1 and 2 subjected to 1% SLP

In order to obtain the tuning ability of the proposed controller, the system is analyzed with a 1% step load perturbation subjected to both the areas. In the initial phase of analysis, a 1% step load perturbation to area-1 is applied at t=0 s. In the later stage of analysis, 1% SLP to both areas were applied at t=0 s. The frequency change and tie-line power after a disturbance, are depicted in Figures 7 and 8.

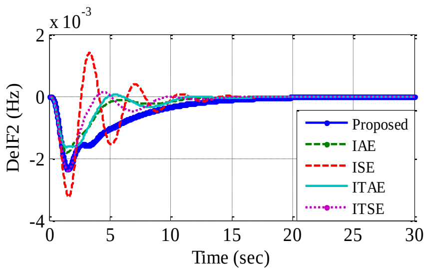

Figure 7. Change in frequency at area 2 with 1% SLP in both area

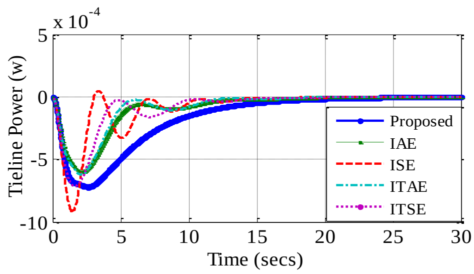

Figure 8. Change in tie-line power exchange with 1% SLP in both area

With 1% SLP subjected at both areas, ISE objective function is having the highest overshoot value for change in frequency at both areas and tie-line power exchange. Due to which system with ISE function takes time to settle for all other considered functions. From Table 4, it is noted that change in frequency and tie-line power exchange with 1% SLP applied at both areas then obtained ISE function is followed by ITSE, ITAE, IAE, and proposed function.

Therefore, the proposed function with CSO were having the least settling time value as 2.27 sec and ISE function is having the highest settling time value as 5.66 sec. It is concluded that the proposed function is performing well with CSO algorithm in both the cases having minimum % peak overshoot as 1.4 and minimum settling time as 2.27 sec compared to PSO algorithm.

Table 4. Overshoot and settling time with 1% SLP at area 1 and 2

	Overshoot (%)			Settling time (sec)				Overshoot (%)			Settling time (sec)		
Case	ΔF1	ΔF2	ΔP12	ΔF1	ΔF2	ΔP12	Case	ΔF1	ΔF2	ΔP12	ΔF1	ΔF2	ΔP12
PSO	1.35	1.10	1.8	1.25	2.40	2.45	CSO	0.99	0.93	1.4	1.07	2.16	2.27
IAE	1.65	1.40	2.15	2.20	3.15	2.65	IAE	1.42	1.23	1.93	1.82	2.97	2.33
ISE	2.02	1.85	2.45	2.34	6.14	6.25	ISE	1.89	1.46	1.99	1.93	5.57	5.66
ITAE	1.75	1.45	2.25	2.25	3.21	2.75	ITAE	1.47	1.28	1.98	1.82	2.32	2.33
ITSE	1.68	1.95	2.10	1.35	2.82	2.70	ITSE	1.42	1.68	1.95	1.18	2.62	2.31

4.3. Sensitivity analysis

Sensitivity analysis is carried by the varying input signal and system parameters. The test case was equipped with two phases. In first phase, an arbitrary load pattern is considered to make test conditions more sensible towards practical load uncertainties. This is applied to area-1 of the test system to demonstrate the competence and robustness of the objective function. The time constant of system parameters is varied in the range of ±50% with a step change of 25%. The system performance under these parametric uncertainties is shown in Figures 9-14. To validate the performance of the suggested objective function for additional objective functions, a random load signal was applied to the test system. According to Figures 9-14, the suggested objective function outperforms the other objective functions in terms of overshoot and settling time values of frequency change and tie-line power exchange. System parameters are varied from -50% to +50% with 25% step change. From Table 5, it is noted that when system parameters are varied to -25%, ISE is less oscillatory compared to ITSE, ITAE, and IAE. However, the proposed function performance is non-oscillatory, as per Figures 9-14 and has the least overshoot value and settling time at area-1 and area-2 compared to ISE, ITSE, ITAE, and IAE. With -50% parameter variation overshoot values are arranged in ascending order as proposed function, IAE, ITAE, ITSE, and ISE. With +25% parameter variation, among all ISE is having adverse performance. ISE performance is high in oscillations magnitude of error increasing with time, which leads the system to an unstable state.

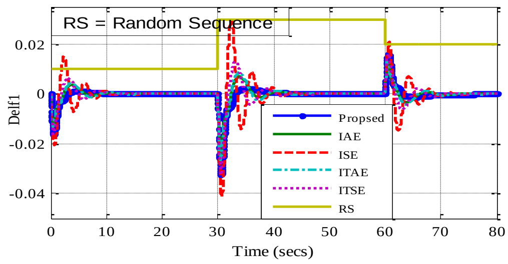

Figure 9. Change in frequency at area-1 with random load pattern

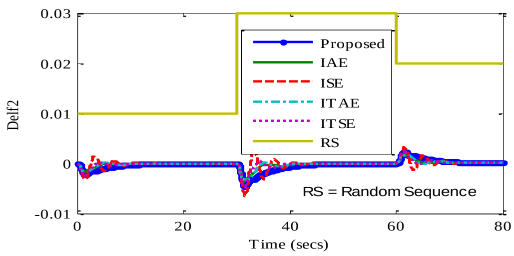

Figure 10. Change in frequency at area-2 with random load pattern

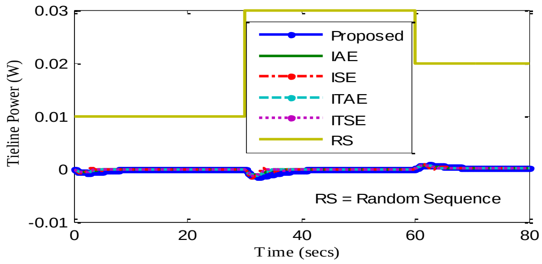

Figure 11. Change in tie-line power with random load pattern

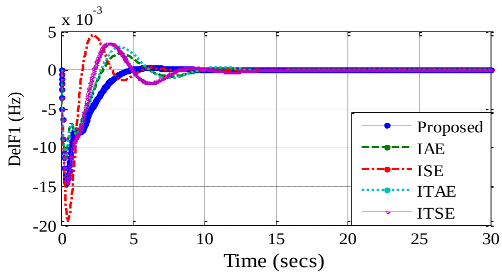

Figure 12. Change in frequency at area-1 with -25% parameter variation

ITSE also follows the ISE performance but not that adverse compared to ISE due to time multiplier in the objective function of ITSE. When system parameter variation is +25%, IAE, and ITAE are less sensitive as compared to proposed function. Even with +25% system parameter variation proposed function has the least overshoot and settling time values. With +50% system parameters, ISE and ITSE performance is very adverse compared to all other like IAE, ITAE and proposed function. Therefore, the proposed function has the least overshoot and settling time compared to all other objective functions and less sensitive to parameter variations. Overshoot and settling time values of the proposed function are tabulated in Table 5. This is achieved due to the contribution of overshoot and settling time as tuning variables in the proposed objective function as per (5).

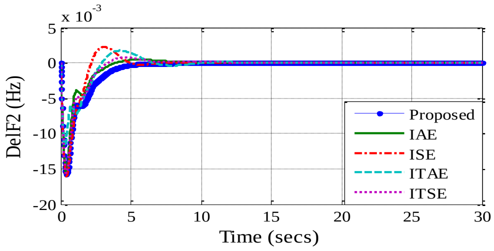

Figure 13. Change in frequency at area-2 with -25% parameter variation

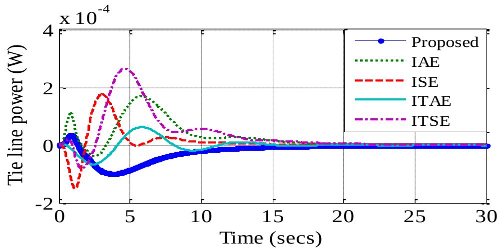

Figure 14. Change in tie-line power with -25%

Table 5. Overshoot and settling time of proposed function with system parameter variation

	Overshoot (%)			Settling time (secs)		
Parameter variation (%)	ΔF1	ΔF2	ΔP12	ΔF1	ΔF2	ΔP12
-50	1.134	0.91	1.748	1.1	2.24	2.38
-25	1.137	0.89	1.755	1.09	2.19	2.35
0	0.99	0.93	1.414	1.07	2.16	2.27
25	1.104	1.022	1.644	1.24	2.17	2.39
50	1.14	1.114	1.694	1.3	2.45	2.58

5. CONCLUSION

This paper introduces a novel time-domain multi-objective function that utilizes the CS optimization algorithm to enhance the dynamic stability of interconnected power systems. The study focuses on a two-area thermal power plant, each equipped with its own PID controller, to evaluate the objective function's potential in minimizing overshoot and settling time during system oscillations. Simulations involve a 1% step load perturbation, first in area-1 and then simultaneously in both areas. Results indicate that the proposed time-domain objective function can achieve an average reduction of 15% in overshoot and 6% in settling time. The proposed objective function's performance has been compared to other integral-based objective functions, and the findings are intriguing. Furthermore, sensitivity analysis were performed to illustrate the robustness of the objective function in comparison to existing integral error based objective functions. From the analysis, it is observed that the proposed time-domain objective function yields attractive performance in terms of reducing overshoot and settling time of system oscillations under various challenging conditions.

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