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Crow Search Algorithm-Optimized Cascade Controller in a Multi-Area Thermal Wind Integrated System and Its Real-Time Validation

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ABSTRACT

This article explores the load frequency control (LFC) problem for manifold areas and sources under conventional situations. An attempt has been made to demonstrate the solicitation of a real-time simulation laboratory for the LFC studies of three thermal area systems. Thermal systems are integrated with renewable like wind systems in area-1, 2 respectively. A novel ancillary controller termed by cascade tilt integral-proportional integral derivative (TI-PID) is suggested and is augmented by crow search algorithm. The superiority of TI-PID controller is tested and found to be better with PID and tilt integral derivative (TID) controller. Moreover, the obtained responses with hybrid peak area-integral square error are compared with ISE, and it shows better responses over ISE. Further, the responses with alternating current-high-voltage direct-current system improve system dynamics over wind-thermal and thermal systems. Furthermore, sensitivity analysis suggests that the TID with filter controller considerations attained at nominal circumstances are vigorous.

***Index Terms*—**Load frequency control, cascade controller, hybrid peak area-integral square error, crow search algorithm, wind system

Nomenclature	
ΔF, ΔP_{tie}	Frequency and tie-power variation
R_j	Regulation parameter (Hz/ p.u. MW)
a_{jk}	$-(P_{rj}/P_{rk})$
T_{tj}, T_{gj}, T_{rj} and T_{WTSj}	Governors, turbine, reheat and WTS time constant
K_{rj}, $K_{WTS,j}$	Coefficient of reheat and WTS turbine
K_{Tij}, K_{Pij}, K_{Iij}, $K_{Dij,}$	Tilt, proportional, integral, derivative and filter gains of T/PIDN controller

I. INTRODUCTION

The primary use of load frequency control (LFC) is to diminish the misalliance amid the load and generation units [1]. Violation of this misalliance inclines to abnormalities in frequency and power. The prompt LFC works started through sole [2] and protracted to multiarea works [3]. [4, 5] demonstrated an LFC study with generator rate constraints (GRC) and governor dead band. The excess emission of carbon fuels and decrement of fossil fuels tends to the penetration of renewable energy sources. Renewable energy sources like Wind, solar dictates over others. Authors in [6-10] presented the integration of wind [6], solar thermal power plant [7-9], and dish-Stirling solar thermal system [10] with solitary of thermal two-area. Hence, the amalgamation of wind in three-area systems necessities investigations.

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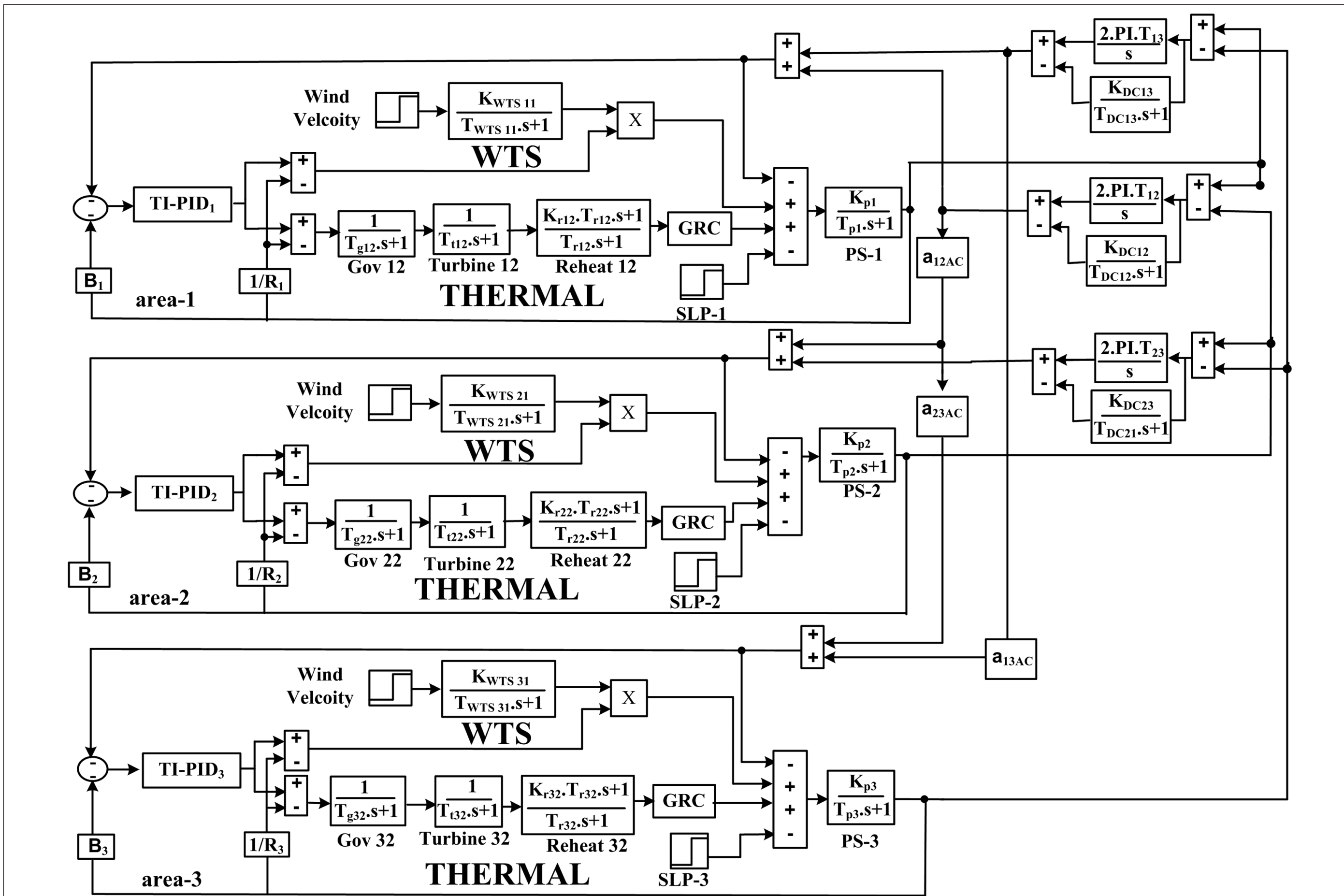

Fig. 1(a). System investigated.

During abnormal conditions, system dynamics will be weakened. Moreover, in long transmission lines, dynamics will be further deteriorated owing to the existence of transients in frequency and power. These deteriorations can be stamped out by the incorporation of high-voltage direct-current (HVDC) [11-13]. Sharma et al. [14, 15] demonstrated an LFC study with parallel alternating current (AC)-HVDC systems. However, the above LFC systems considering AC-HVDC systems [11-15] are of two-area conventional and deregulated power systems only [16]. Further, these studies did not include renewable generation.

The present LFC study focuses on the scheme of secondary controllers. They help in abolishing the inaccuracies. Controllers like proportional integral derivative (PID) with filter [17], fractional order PID [18], tilt integral derivative (TID) [19], and cascade [8] are utilized for LFC. Also, controllers like degree of freedom [20], fuzzy [21, 22], and artificial neural networks [23] are successfully applied for LFC studies. A novel cascade combination of tilt integral with PID (TI-PID) is suggested and has not been reported previously. Evolutionary and classical techniques are necessary for augmented controller tuning. Tuning by classical technique is arduous and time-consuming, while

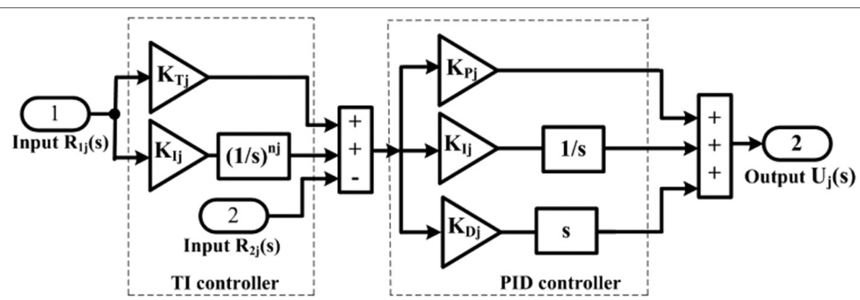

Fig. 1(b). TI-PID controller.

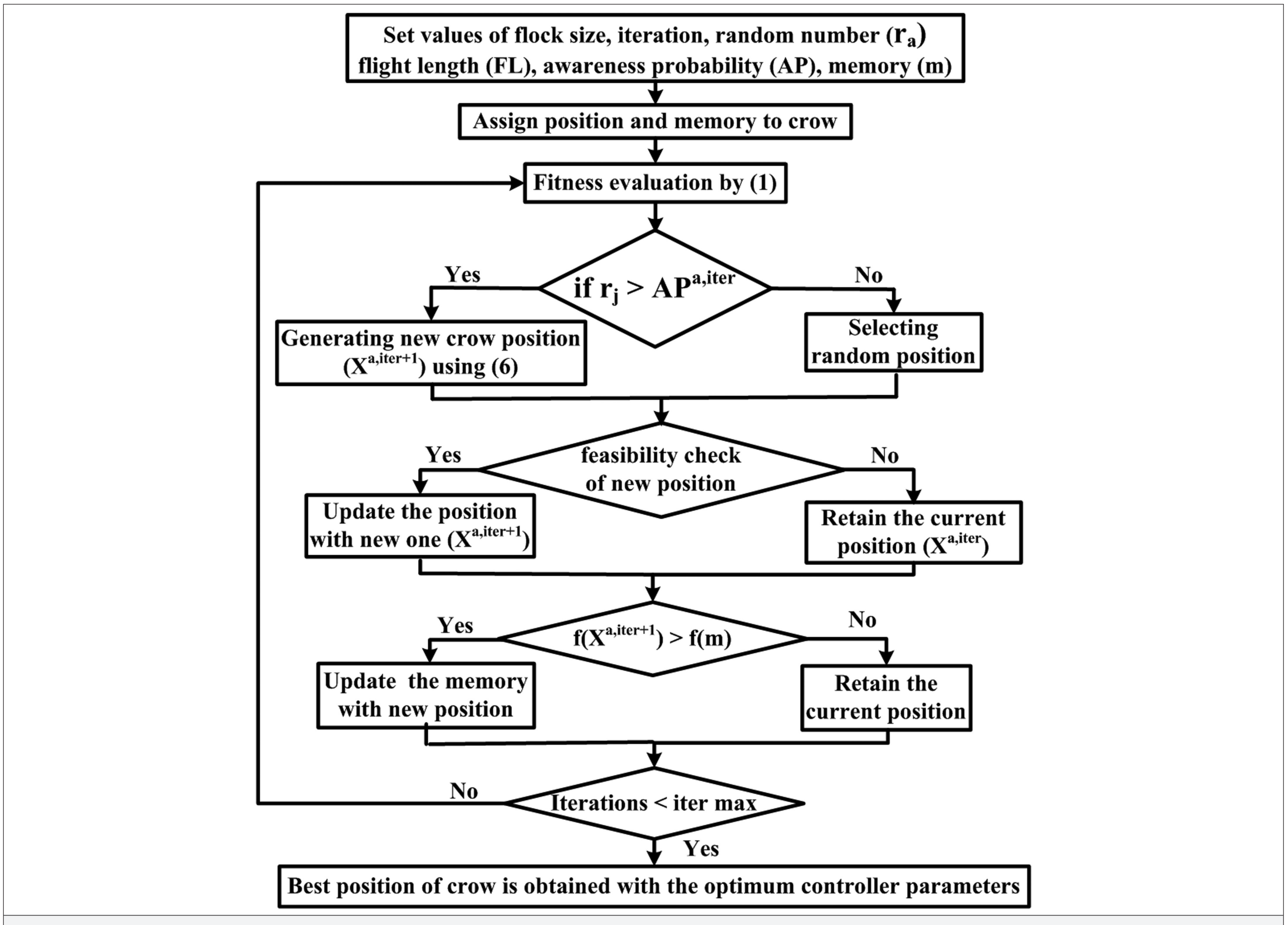

Fig. 1(c). CSA flow chart.

Evolutionary Algorithms (EAs) deliver optimal consequences. EAs like genetic[3], whale [6], firefly [24], biogeography [25], particle swarm [26], coyote optimization [27], hybrid whale [28], slime mould [29],

Fig. 2. RT-Lab experimental setup.

TABLE I. CSA-AUGMENTED CONTROLLER GAINS OF THERMAL SYSTEM WITH HPA-ISE

PID

	K_{Pj}	K_{Ij}	K_{Dj}
A_1	0.4066	0.3920	0.1843
A_2	0.7380	0.1120	0.8466
A_3	0.9580	0.1694	0.3752

TID

	K_{Tj}	s_j	K_{Ij}	K_{Dj}
A_1	0.6212	4.2090	0.9993	0.3713
A_2	0.0591	3.6985	0.5217	0.4564
A_3	0.4612	4.8450	0.6163	0.7261

TI-PID

	K_{Pj}	K_{I1j}	K_{Tj}	s_j	K_{I2j}	K_{Dj}
A_1	0.4841	0.8209	0.3167	5.0136	0.0571	0.3288
A_2	0.5802	0.1797	0.8103	7.1903	0.4100	0.8729
A_3	0.5981	0.6388	0.7724	6.2639	0.8801	0.7384

A, area; CSA, crow search algorithm; HPA-ISE, hybrid peak area-integral square error; PID, proportional integral derivative; TID, tilt integral derivative; TI-PID, tilt integral-proportional integral derivative.

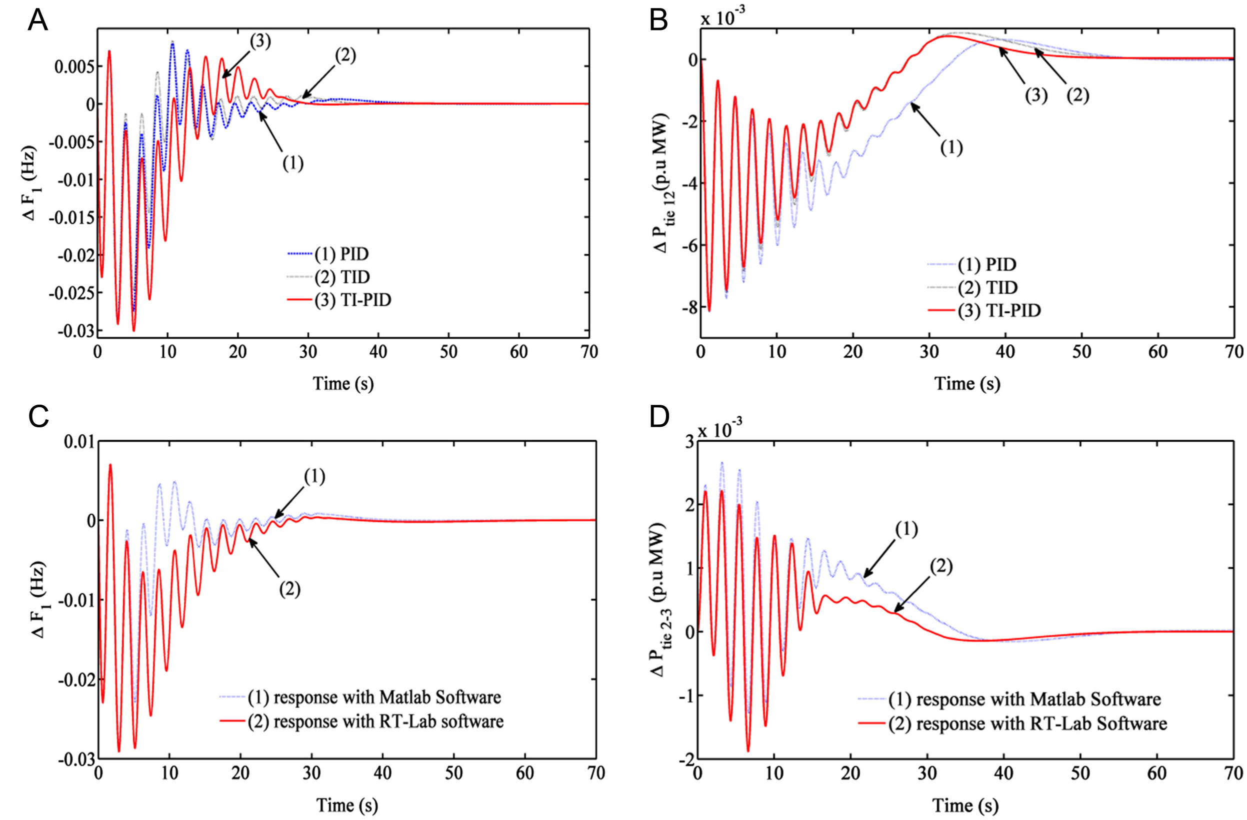

Fig. 3. A-D. Thermal system dynamics; MATLAB response (A) ΔF_1, (B) ΔP_{12}, (C) ΔF_1, and (D) ΔP_{23} with MATLAB and RT-Lab.

improved particle swarm [30], etc., are accessible for LFC studies. The latest evolutionary entitled by crow search algorithm (CSA) [31-34] works on the nutrition hunt actions of crow. Surprisingly, the application of CSA is to be evaluated in LFC studies.

The above-stated LFC studies [2-25] have mostly utilized ISE as a performance index. Pathak et al. [35] have proposed a hybrid peak area-integral square error (HPA-ISE) as a performance index which focuses on the reduction in peak values. Authors in [4, 36-38] have presented sensitivity analysis (SA) by the disparities in system parameters like loading condition from nominal standards, though SA of CSA augmented TI-PID controller is not stated.

The above-specified LFC studies remain replicated in MATLAB software though, from the literature, its validation in a real-time simulation laboratory (RT-Lab) is not carried out. This offers the opportunity for imminent assessments.

The intents are as follows:

a) To expand a thermal system with wind and AC-HVDC.
b) Solicitation of CSA process for augmentation of controllers.
c) To perform SA with superior controller.
d) To study the effect of AC-HVDC system.
e) Validation in RT-Lab software.

A. Novelty of Work

From above, the novelties are as follows:

a) The enactment evaluation of Wind turbine systems (WTS)-HVDC-based thermal LFC system is carried.
b) Intention of a novel cascade TI-PID controller in LFC studies.
c) Application of HPA-ISE in AGC studies.
d) An initial effort was made to deportment the SA.
e) Solicitation of CSA optimization for the instantaneous controller optimization.

TABLE II. CSA-OPTIMIZED CONTROLLER GAINS OF THERMAL SYSTEM CONSIDERING ISE

	K_{Pj}	K_{I1j}	K_{Tj}	s_j	K_{I2j}	K_{Dj}
A_1	0.7627	0.4607	0.5315	7.0796	0.6357	0.7575
A_2	0.1299	0.0027	0.8306	4.3735	0.3631	0.4055
A_3	0.3786	0.5406	0.4582	8.9467	0.1374	0.64530

A, area; CSA, crow search algorithm; ISE, integral square error.

TABLE III. CSA-OPTIMIZED CONTROLLER GAINS WITH INTEGRATION OF WIND SYSTEMS

	K_{Pj}	K_{I1j}	K_{Tj}	s_j	K_{I2j}	K_{Dj}
A_1	0.0230	0.1222	0.1164	2.0970	0.0417	0.2482
A_2	0.1466	0.3136	0.3307	7.0064	0.8992	0.4131
A_3	0.7176	0.5498	0.0575	2.0224	0.3975	0.5370

A, area; CSA, crow search algorithm.

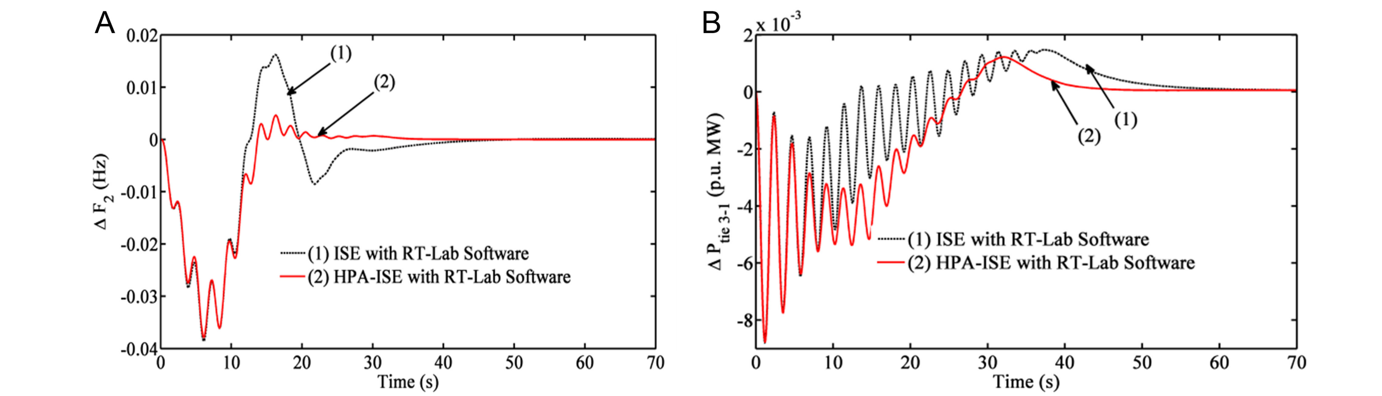

Fig. 4. A, B. Dynamics with ISE and HPA-ISE: (A) ΔF_2 and (B) ΔP_{31}.

B. Contribution

The foremost contributions of the article are as follows:

a) Studies are conceded with wind-HVDC considering conventional thermal AGC system.
b) A new cascade TI-PID is projected and its concert is found to be improved over PID and TID controllers.
c) Controller parameters are optimized by the CSA technique with HPA-ISE and enhance the system dynamics over ISE techniques.
d) SA suggests that the controller parameters obtained at nominal conditions are robust.

The article is organized as follows. Section I describes the literature survey, research gap, novelty, and contributions. System investigated and the proposed cascade TI-PID controller are explained in sections II and III. Section IV describes the CSA, Results are explained in Section V, and section VI concludes the article.

II. SYSTEM INVESTIGATED

The system includes a thermal-wind system with capacities of 1:2:3 integrated with HVDC. GRC of 3%/min and droop of 4% are considered in thermal systems for a realistic approach. Figure 1(a) shows the system probed with CSA-optimized TI-PID controller. Controllers such as PID, TID, and the proposed TI-PID are considered. Its gains are augmented by CSA considering HPA-ISE and are given by (1), [35, 39].

$$\bullet\ _{HPA\text{-}ISE}=\int_0^t \{(\Delta F_j)^2+(\Delta P_{j\text{-}k})^2+|\Delta F_{j,\,peak}|+|\Delta P_{j\text{-}k,\,peak}|\}.dt \qquad (1)$$

Studies are performed using (a) thermal system in MATLAB [40] and RT-Lab software, (b) thermal system with HPA-ISE, (c) system-a with wind and HVDC integration, and (d) SA in system-c. Controllers like TID, PID, and cascade TI-PID are deliberated individually with step perturbation in area-1. Values of thermal, wind, and HVDC are in Appendix.

III. PROPOSED CASCADE TI-PID CONTROLLER

A novel cascade controller viz. TI-PID is suggested, which is a combination of integer and tilt controllers. The transfer function (TF) of TI-PID is in (2, 3).

$$TF_{TI}=K_{Tj}(1/s)^{n_j}+K_{Ij}/s \qquad (2)$$

$$TF_{PID}=K_{Pj}+K_{Ij}/s+K_{Dj}.s \qquad (3)$$

The structure of TI is the same as that of the PID controller with a multiplying factor of $(1/s)^n$. Six parameters are considered for optimization. The TF diagram of TI-PID controller is in Fig. 1(b). The gains are augmented by CSA in (4).

$$\begin{gathered}0\le K_{Tj}(\text{Tilt})\le 1, 0\le K_{Pj}(\text{Proportional})\le 1, 0\le K_{Ij}, K_{I1j}(\text{Integral})\le 1\\ 0\le n_j(\text{real})\le 7 \text{ and } 0\le K_{Dj}(\text{Derivative})\le 1\end{gathered} \qquad (4)$$

IV. CROW SEARCH ALGORITHM

Alireza Askarzadeh proposed CSA [27]. The ability of face recognition, tools usage, storing, and hiding of food sorts a crow an intellectual fowl. For food search, CSA generates d-dimension solution set. The possible search agent's solution set is in (5), [34].

$$[X^{y,iteration}=X_1^{y,iteration},X_2^{y,iteration},\ldots,X_d^{y,iteration}] \qquad (5)$$

where d is dimension set. The possibilities for crow-z to sojourn eatable dwelling of crow-y are:

Possibility 1: Crow-y approaches crow-z location without knowing and its path is in (6), [34].

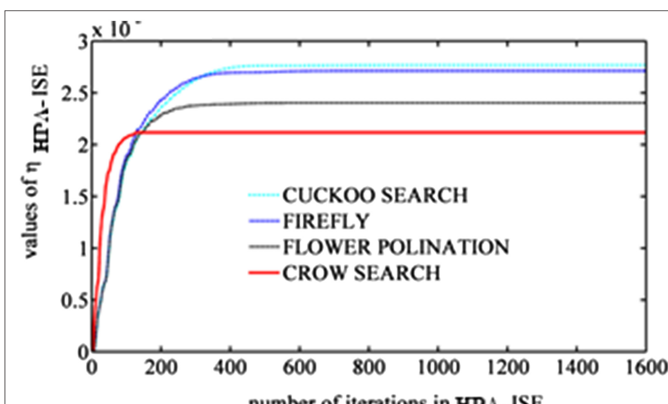

Fig. 5. Convergence characteristics with various algorithms.

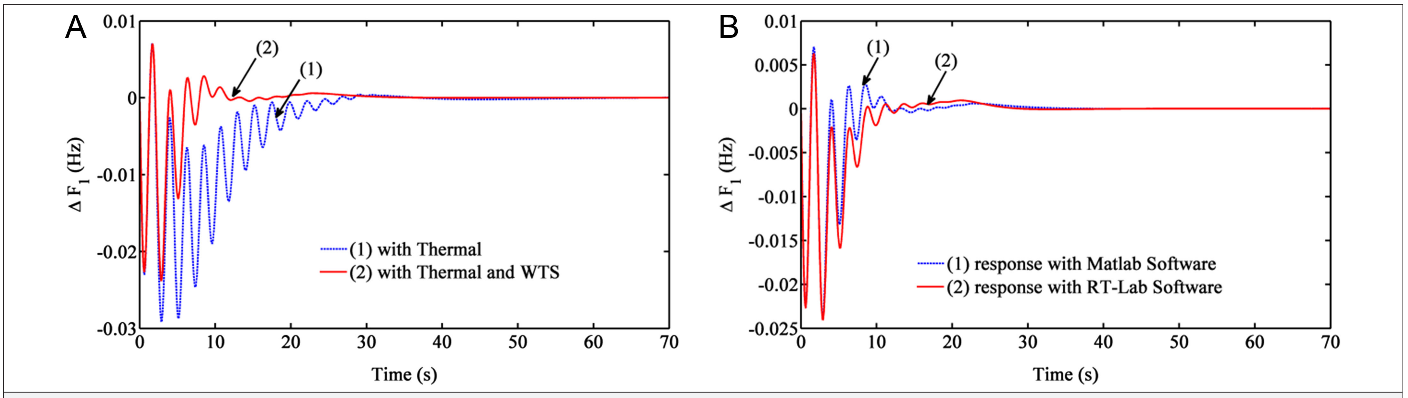

Fig. 6. A, B. Dynamics with thermal-wind: (A) ΔF_1 (MATLAB) and (B) ΔF_1 (RT-Lab).

$$X^{y,\text{iteration}+1} = X^{y,\text{iteration}} + r_y \times \text{Flight Lenght}^{y,\text{iteration}} \times \left(m^{z,\text{iteration}} - X^{z,\text{iteration}}\right) r_b \geq AP^{z,\text{iteration}} \quad (6)$$

where r_b and r_y are random values. With the smaller reduction in awareness probability, CSA provides the finest solution.

Possibility 2: Expressive crow-z approach, crow-y sailed to an arbitrary location

In iteration, crow's finest solution is stowed. If the contemporary solution is deemed to be superior over the previous elucidation, it automatically gets renewed and is stored until termination criteria. Figure 1(c) shows CSA flowchart.

In this present work, the proposed TI-PID controller gains (e.g., K_{Tj}, K_{Ij}, n_j, K_{Pj}, K_{I1j}, K_{Dj}, and N_j) are instantaneously augmented by using CSA considering HPA-ISE as the performance index.

TABLE IV. CSA-OPTIMIZED CONTROLLER GAINS WITH HVDC SYSTEMS

	K_{Pj}	K_{I1j}	K_{Tj}	s_j	K_{I2j}	K_{Dj}
A_1	0.7423	0.1084	0.5779	0.9268	0.2111	0.2497
A_2	0.1525	0.0019	0.8729	0.5243	0.4298	0.8548
A_3	0.7507	0.0389	0.9579	0.8559	0.4603	0.7561

A, area; CSA, crow search algorithm; HVDC, high-voltage direct-current.

V. RESULTS AND ANALYSIS

The performance of the thermal-wind-HVDC system is provided with TID, PID, and TI-PID. The LFC system is evaluated in MATLAB and validated with RT-Lab Software using ode4. The CSA-optimized controllers with the finest values are allied with RT-Lab, and the results are to be compared with MATLAB and are demonstrated in Fig. 2.

A. System Dynamics With Thermal System

1) Controller Assessment in Thermal Systems

The three-area thermal system with a capacity ratio of 1:2:4 is provided with TID, PID, and TI-PID controllers with CSA optimization and HPA-ISE. The obtained optimum gains are in Table I and their respective responses are in Fig. 3(a) and (b). The obtained dynamics are compared with the results from RT-Lab in Fig. 3(c) and (d).

Careful interpretations of Fig. 3 discover that responses with TI-PID exhibit better. Further, the responses with RT-Lab show better dynamics over MATLAB.

2) Analogy Among HPA-ISE and ISE:

The thermal system with TI-PID controller with ISE is examined. CSA-augmented gains are in Table II. The obtained dynamics in RT-Lab are compared with the thermal of section 1(a) and are in Fig. 4. It is perceived that the responses with HPA–ISE gives better system dynamics over ISE.

3) Comparison Among Crow Search Algorithm With Various Contemporary Algorithms:

The thermal system with TI-PID controller considering HPA-ISE is subjected to various algorithms like cuckoo search, firefly, flower

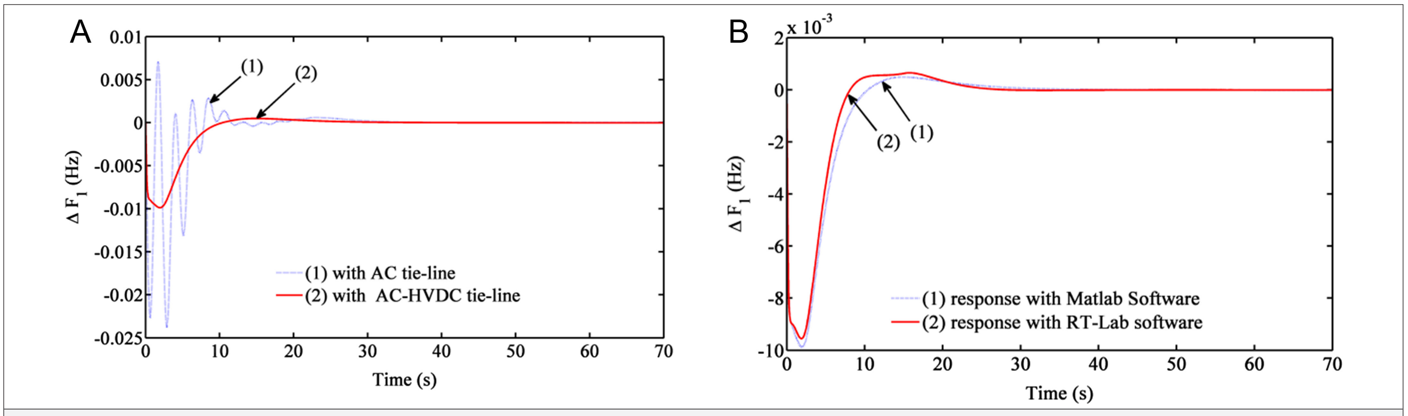

Fig. 7. A, B. Dynamics with HVDC: (A) ΔF_1(MATLAB) and (B) ΔF_1 (RT-Lab).

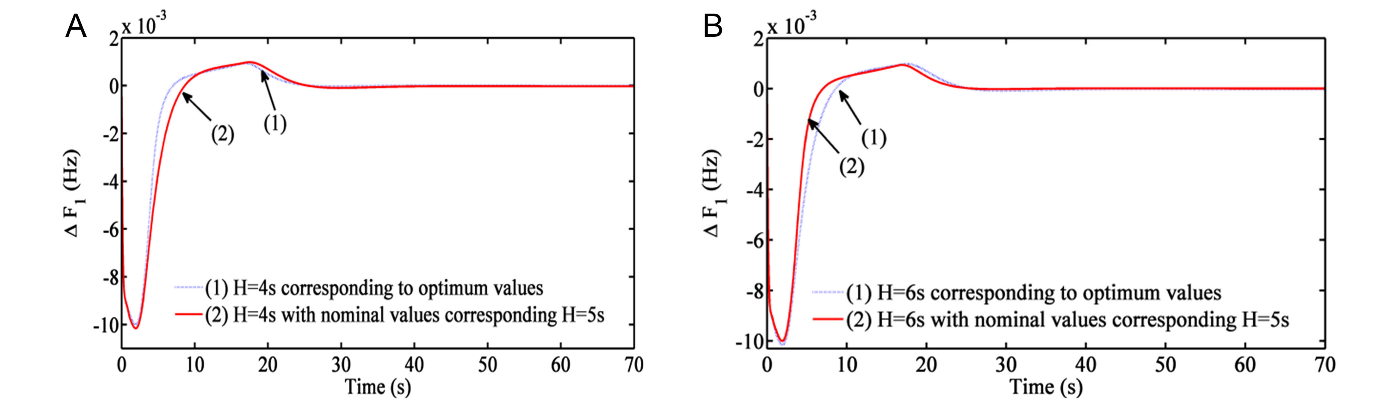

Fig. 8. A, B. Dynamics at SA condition: (A) ΔF_1 and (B) ΔP_{12} with RT-Lab.

pollination, and the proposed CSA technique. The optimum values with various algorithms are not shown. The obtained system dynamics with various algorithms are compared in Fig. 3, and it is observed that the responses with CSA converge faster than other algorithms. Fig. 5. is the result obtained from thermal systems considering various algorithms like the crow search algorithm, cuckoo search algorithm, firefly algorithm, and flower pollination algorithms.

B. Effect of Wind System

The thermal system in section 5.1 is integrated with wind systems in all the areas. TI-PID controller is provided and is optimized with CSA technique. Its augmented gains are listed in Table III. The attained dynamics with MATLAB are likened with the results from section 5.1.2. The MATLAB responses are compared with RT-Lab software in Fig. 6. Cautious remarks explore that the responses with wind integration show better responses. Further, responses in Fig. 6(b) show that responses with RT-Lab provide better responses over MATLAB software.

C. Impact of HVDC

The system in Fig. 1(b) is equipped with CSA-augmented TI-PID controller. Table IV shows the augmented values. Responses considering HVDC systems in MATLAB software are in Fig. 7(a). The dynamics with the HVDC system considering MATLAB software are compared with RT-Lab and shown in Fig. 7(b). It is perceived that HVDC system dynamics considering RT-Lab software show better responses.

D. Sensitivity Analysis With TI-PID Controller

The system in Fig. 1 is considered and is exposed to disparities with inertia constant (H), that is, ±15% from ostensible value. TI-PID controller is added and investigations are carried out in RT-Lab software and assessed in Fig. 8. Assessment of Fig. 8 shows that the responses obtained are almost similar and require no further amendments.

VI. CONCLUSION

The attempt of RT-Lab software in LFC studies has shown success. In LFC research, a novel index named with HPA-ISE is used. Also, a novel optimization termed CSA is considered for controller augmentation. From the details mentioned earlier, the conclusions of the article are as follows:

- Studies with TI-PID controller outperforms others like PID and TID controllers in terms of a 20% increase in settling time and peak deviations.
- Also, the dynamics with HPA-ISE outcomes over ISE show 30% better values of settling time.
- Moreover, the integration of wind in thermal systems shows a 30% increase in better responses over thermal.
- Further incorporation of HVDC with AC improves system dynamics by 20%.
- SA with inertia variations suggests that the proposed TI-PID controller is robust.
- Furthermore, the system dynamics obtained with MATLAB are validated with RT-Lab software and its responses outperform over MATLAB software.

Similarly, in the coming days, the overhead projected method of LFC can also be applied in the combined control of voltage and frequency by connecting an automatic voltage regulator with the proposed LFC system. Besides, it can be applied with combinations of other artificial intelligence techniques.

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APPENDIX

Nominal system Parameters: F = 60 Hz, $T_{jk,AC}$ = 0.086 pu MW/rad, H_j = 5s, K_{pj} = 120 Hz/MW pu, D_j = 8.33 × 10^{-3} pu MW/Hz, B_j = 0.425 pu MW/Hz, R_j = 2.4 pu MW/Hz, T_{gj} = 0.08s, T_{tj} = 0.3 s, T_{rj} = 10 s, K_{rj} = 0.5 s, T_{pj} = 20 s, Ks_j = 1.8, Ts_j = 1.8 s, SLP = 1%, loading = 50%, P_{r1} = 1000 MW, P_{r2} = 2000 MW, K_{DC} = 0.5, T_{DC} = 0.03 s. Crow search optimization: Flock size = 50, flight length = 0.2, awareness probability = .1, maximum generation = 100.