

APPLICATION OF CASCADE TI-TID CONTROLLER IN A TWO-AREA RENEWABLE INTEGRATED AGC SYSTEM USING BSA ALGORITHM

Rambabu Kasukurthi*, and R. Srinu Naik

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Abstract

This study marks the first effort to optimize controller parameters for Automatic Generation Control (AGC) using the Bird Swarm Optimization (BSA) algorithm, a novel metaheuristic technique. A secondary cascade controller, TI-TID, is introduced for a two-area AGC system. Simulation outcomes reveal that the TI-TID controller surpasses conventional PI and PID controllers by achieving better settling time, peak overshoot, and peak undershoot. The integration of Solar Thermal Power Plant Systems (STPPS) and a High Voltage Direct Current (HVDC) link significantly improves system dynamics. Furthermore, a sensitivity analysis under different loading conditions confirms the sturdiness of the projected controller, which consistently maintains stable dynamic behavior despite variations in load. Further, studies with automatic voltage regulator (AVR) loops over AGC reveal improved dynamics.

Keywords: AGC, BSA, Cascade controllers, STPPS, AVR

Nomenclature

AGC	Automatic generation control
AVR	Automatic voltage regulator
BSA	Bird swarm optimization
TI-TID	Tilt integral-tilt integral derivative
PID	Proportional integral derivative
ST	Settling time
PU	Peak undershoot
PO	Peak overshoot
STPPS	Solar thermal power plant system
HVDC	High-voltage direct current
F	Frequency
P	Power
m, n	Area numbers
GRC	Generation rate constraints

Introduction

Maintaining a stable equilibrium between generation-demand demand presents growing challenges with modern power grid's increasing scale and complexity. Keeping the system frequency within prescribed limits further intensifies this difficulty (Kundur, 2007). AGC plays a pivotal role in mitigating these issues by dynamically regulating power outputs across multiple control areas to uphold a stable frequency and ensure overall system stability (Elgerd, 2007). While early research on AGC centered on single-area thermal systems, recent efforts have expanded toward more sophisticated configurations involving

Department of Electrical Engineering, Andhra University College of Engineering, Andhra University, Visakhapatnam 530003, India.
Email: rambabu.kasukurthi@gmail.com*; naiknaiknaik@gmail.com

* Corresponding author

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multi-area and multi-source networks (Elgerd and Fosha, 2007; Bhagat *et al.*, 2020; Meseret and Saikia, 2024). Furthermore, earlier studies have also incorporated real-world nonlinearities, such as generation constraints and communication or control delays.

Numerous AGC studies have concentrated on the efficient amalgamation of renewables, including wind turbine systems (WTS) (Saha and Saikia, 2017; Sharma and Saikia, 2015) and solar thermal power plant systems (STPPS) (Tasnin and Saikia 2018; Bhagat *et al.*, 2023). Studies such as Bhagat *et al.* (2023) and Chidambaram and Paramasivam (2013), analyzed two-area AGC systems incorporating WTS, while assuming a constant wind speed. However, the power output from STPPS is naturally variable due to fluctuations in solar irradiance. Although power electronic converters can mitigate some of this variability, limited research has addressed the integration of STPPS within AGC frameworks. In response to this gap, the present paper explores the incorporation of STPPS alongside traditional thermal systems to improve AGC performance.

Power system performance tends to decline under abnormal operating conditions, with dynamic responses further compromised by transients in long transmission lines. One effective strategy is the incorporation of high-voltage direct current (HVDC) links (Chidambaram and Paramasivam, 2013; Jagatheesan *et al.*, 2017). Although AGC studies involving HVDC integration are still relatively scarce, Chidambaram and Paramasivam. (2013) have emphasized the benefits of employing such links. These insights can be extended to more complex arrangements, such as two-area systems, especially when integrating HVDC into the overall power system.

Research on AGC has focused mainly on the advancement of auxiliary controllers. Over the years, a variety of supplemental controllers have been proposed, including basic fractional-order controllers, cascade controllers, and tilt-based controllers such as PI-PD (Dash *et al.*, 2016), PI-PID (Jagatheesan *et al.*, 2017), and TID controllers (Babu *et al.*, 2019). However, different structural configurations of the TID controller have yet to be explored in AGC applications. To address this gap, this paper proposes a new cascade controller that combines a TI controller with a TID controller, referred to as the TI-TID controller.

Recent developments in AGC research have highlighted the effective use of various optimization algorithms, such as whale (Saha and Saikia, 2017), Grey Wolf (Sharma and Saikia, 2015), sine cosine (Tasnin and Saikia 2018), crow (Babu *et al.*, 2019), particle swarm (Pan and Das, 2015), hybrid crow (Babu *et al.*, 2020), genetic (Golpira and Bevrani,

2011), ant lion (Saikia *et al.*, 2017), Cuckoo Search (Dash *et al.*, 2015), firefly (Saikia *et al.*, 2013), crow search (Babu *et al.*, 2024; Babu *et al.*, 2025), moth fly (Chiranjeevi *et al.*, 2025), tunicate swarm (Saha *et al.*, 2024), reinforcement learning (Li *et al.*, 2025; Chen *et al.*, 2025), and hawk optimization (Awal *et al.*, 2025). Among these, BSA has shown notable improvements in controller performance across various AGC configurations. Xian *et al.* (2016) introduced the BSA algorithm, inspired by the cooperative foraging behavior of bird swarms. This method achieves global optimization with fewer iterations and offers high accuracy and rapid convergence (Bhagat *et al.*, 2021; Bhagat *et al.*, 2024). Nevertheless, its potential for optimizing a PID-TID controller within a two-area AGC system remains unexplored.

Sensitivity analysis in AGC studies is commonly performed to evaluate the robustness of controllers under substantial load variations (Kundur, 2007; Elgerd, 2007). Although the present work proposes a novel controller-namely the TID controller with a filter-a comprehensive sensitivity analysis has not yet been conducted, highlighting an opportunity for future research. Accordingly, the objectives of this study are: (a) to develop a two-area AGC system incorporating thermal and STPPS components; (b) to implement multiple controllers within the system, including TI, TID, and the cascade TI-TID controller; (c) to employ BSA for concurrent optimization; (d) to assess system dynamic responses resulting from STPPS integration; (e) to investigate system dynamics under HVDC link integration; (f) to conduct a sensitivity-based robustness evaluation of the proposed controller; and (g) to examine the impact of the AVR.

Novelties and Contributions

The novelties of the article are as follows:

- (a) To develop a novel cascade TI-TID controller for AGC-AVR studies.
- (b) Apply the BSA technique to controller optimization.
- (c) To integrate renewable like STPPS in the AGC-AVR system comprising HVDC for the first time.
- (d) To study the impact of HVDC and AVR.
- (e) To perform a sensitivity analysis with the TI-TID controller.

The contributions of the article are as follows:

- (a) A study is conducted for the first time by incorporating STPPS and HVDC into AGC-AVR analysis.
- (b) A new cascade controller, TI-TID, is proposed for a system with thermal-STPPS and HVDC integration, demonstrating superior

- performance compared to conventional controllers.
- (c) The controller gains in AGC are optimized for the first time using the BSA metaheuristic algorithm.
- (d) To study the impact of the STPPS model integrated with a thermal system in AGC-AVR studies.

Investigated System

Two-area thermal system, consisting of unequal areas and integrated with a STPPS, is modeled using a transfer function representation in Figure 1. The nominal system parameters, sourced from references (Tasnin and Saikia 2018) and (Babu *et al.*, 2025), are provided in the appendix. Various secondary controllers, namely TI-TID, TID, and TI, are individually implemented to investigate the system's dynamic. A novel metaheuristic optimization technique, the BSA is employed. The optimization process is grounded on Integral Squared Error (ISE) with 1% load perturbation applied to Area-1 in (1):

$$\eta_{ISE} = \int_0^t \{(\Delta F_m)^2 + (\Delta P_{m-n})^2\}.dt \quad (1)$$

Proposed TI-TID Controller

An interconnected three-area system is considered to analyze the dynamic response, with AGC using fractional-order controllers for frequency regulation. The tilt design extends conventional PID controllers and is based on fractional calculus,

typically defined by Grünwald-Letnikov, Caputo, or the widely used Riemann-Liouville (RL) approach, expressed as (Pan and Das, 2015):

$${}_a D_t^\alpha f(t) = \frac{1}{\Gamma(n-\alpha)} \frac{d^n}{dt^n} \int_a^t (t-\tau)^{n-\alpha-1} f(\tau) d\tau \quad (2)$$

Here, the Euler gamma function ($\Gamma(\cdot)$), with $n-1 \leq \alpha \leq n$, integer (n). The corresponding fractional integral is given by (3) and its Laplace transform of (2) is in (4).

$${}_a D_t^{-\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_a^t (t-\tau)^{\alpha-1} f(\tau) d\tau \quad (3)$$

$$L\{{}_a D_t^\alpha f(t)\} = s^\alpha F(s) - \sum_{k=0}^{n-1} s^k {}_a D_t^{\alpha-k-1} f(t)|_{t=0} \quad (4)$$

For $n-1 \leq \alpha \leq n$, ${}_a D_t^\alpha$ represents the fractional operator, and $L\{f(t)\}$ denotes the Laplace transform. Assuming zero primary circumstances, the system's dynamics described by fractional differential equations yield a transfer function with a non-integer power of s. This study employs the CRONE guesstimate by Oustaloup, which generates a transfer function over a specified frequency range $[\omega_l, \omega_h]$ using zero(z)-pole(p).

$$s^\alpha = K \prod_{n=1}^L \frac{1+(s/\omega_{z,n})}{1+(s/\omega_{p,n})} \quad (5)$$

The tilt controller is an innovative controller that combines the returns of integer and fractional controllers, first introduced in (Tasnin and Saikia

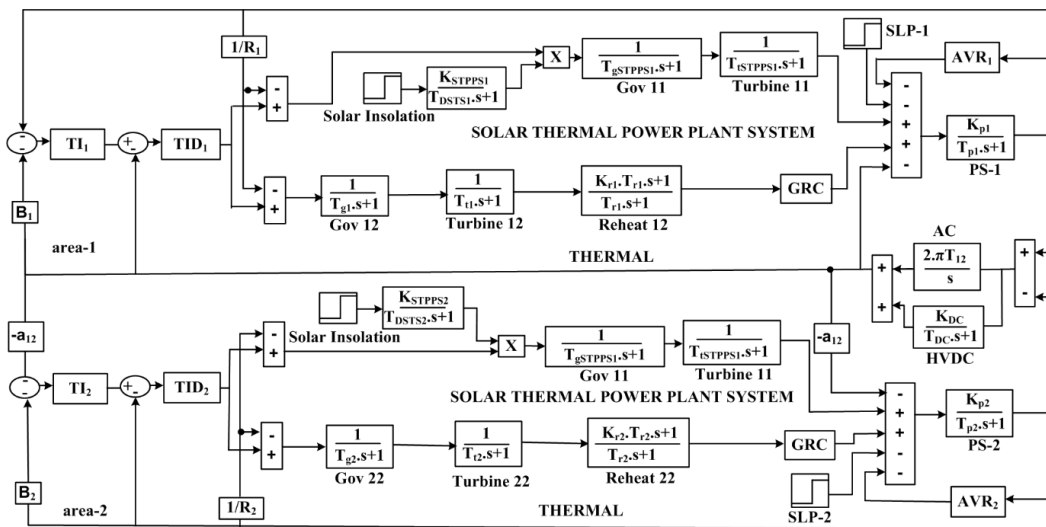


Figure 1. Proposed system model

2018). While the structures of PID and TID controllers are similar, the TID controller introduces a scaling factor of $1/s^n$ to the proportional term of the PID. However, incorporating derivative control within the forward path can lead to the undesired phenomenon of derivative kick in electronic systems (Babu *et al.*, 2019). The mathematical equations for the TI and TID controllers are provided in equations (6) and (7), respectively, while the equation for the cascaded TI-TID controller is given in equation (8), and its diagram is in Figure 2(a).

$$F_1(s) = \frac{K_{T1j}}{\frac{1}{s^{n1i}}} + \frac{K_{I1j}}{s} \quad (6)$$

$$F_2(s) = \frac{K_{T2j}}{1/s^{n2j}} + \frac{K_{I2j}}{s} + K_{D2j}s \quad (7)$$

$$F_{TI-TID}(s) = F_1(s) + F_2(s) \quad (8)$$

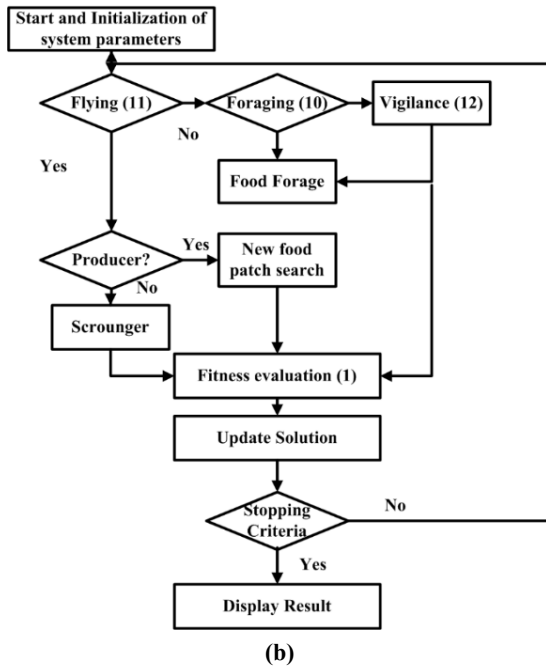
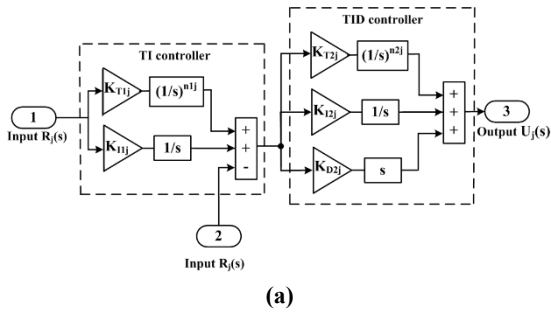


Figure 2. (a) Block diagram of TI-TID controller and (b) BSA working diagram

BSA optimizes controller parameters with constraints in (9).

Bird Swarm Algorithm (BSA)

Meng *et al.* (2016) first introduced the Bird Swarm Algorithm (BSA), inspired by the cooperative behaviors observed in bird flocks and the underlying principles of swarm intelligence. The algorithm represents bird intelligence through essential activities such as foraging, flying, and maintaining vigilance. Accordingly, BSA simulates these behaviors using three primary strategies: (i) food searching, (ii) alertness to potential threats, and (iii) predator avoidance.

Foraging behavior: BSA that birds move toward the global best and personal best positions to exploit reasonable solutions is in (10).

Where present position (x), birds number (p), dimension (q), past position (PP), random (rand), social (t) and cognitive (P) coefficients.

Flight behavior: Dynamics with flight length (fl = 0-2) with alternating roles allow exploration of new regions in the search space and is in (11).

Vigilance behavior: Birds on the outer edge of the swarm are more vulnerable to predator attacks. To minimize this risk, they adopt vigilance behavior and is in (12).

Where fitness (Fit), integer ($0 \leq k$), ($b_1, b_2 \leq 2$) and its flowchart is in Figure 2(b).

Analysis of Simulation Results

To validate the proposed cascade TI-TID controller optimized via the BSA algorithm, simulations were performed on thermal integrated with STPPS and an HVDC tie-line. Using MATLAB/Simulink, the system modeled conventional units, RES, AVR loops, and HVDC dynamics. The BSA was implemented in MATLAB to optimize controller gains by minimizing key performance metrics. The simulation results, compared against traditional TI and TID controllers, demonstrate improved system dynamics, robustness, and frequency regulation under various disturbances and operating conditions.

Assessment of System Behavior for TI, TID, and TI-TID Controllers

Figure 1 presents the system configuration, which incorporates TI, TID, and TI-TID controllers, each used independently as supplementary controllers and heightened using BSA. Optimal values are provided in Table 1. Figure 3 presents a

comparison of controller dynamics. Table 2 summarizes the performance indicators, including POS, PUS, and ST.

A comprehensive examination of Figure 4 and the performance metrics in Table 2 indicates that the TI-TID controller demonstrates superior dynamics over TI and TID controllers. The cascade TI-TID controller will be exploited for the remainder studies.

Evaluation of STPPS Integration Impact on System Performance

In Case 5.1, the system under investigation is equipped with STPPS in each area. The TI-TID controller, identified as the best performer in Case-5.1, is employed, and its optimal parameters are determined using BSA. The optimized TI-TID controller values are presented in Table 3. System dynamics are assessed with the dynamics of a

$$K_{T1j \min} \leq K_{T1j} \leq K_{T1j \max}, n_{1j \min} \leq n_{1j} \leq n_{1j \max}, K_{I1j \min} \leq K_{I1j} \leq K_{I1j \max}, K_{T2j \min} \leq K_{T2j} \leq K_{T2j \max}, n_{2j \min} \leq n_{2j} \leq n_{2j \max}, K_{I2j \min} \leq K_{I2j} \leq K_{I2j \max}, K_{D2j \min} \leq K_{D2j} \leq K_{D2j \max} \quad (9)$$

$$X_{p,q}^{i+1} = X_{p,q}^i + (P_{p,q} - X_{p,q}^m) \times D \times rand_j(0,1) + (g_p - X_{p,q}^i) \times t \times rand_j(0,1) \quad (10)$$

$$X_{p,q}^{j+1} = X_{p,q}^n + randn_i(0,1) \times X_{p,q}^j, X_{p,q}^{i+1} = X_{p,q}^j + (X_{p,q}^j - X_{p,q}^i) \times fl \times rand_i(0,1) \quad (11)$$

$$X_{p,q}^{i+1} = X_{p,q}^i + B_1(mean_q - X_{p,q}^m) \times rand_i(0,1) + B_2(P_{p,q} - X_{p,q}^m) \times rand_i(-1,1) \quad (12)$$

$$B_1 = b_1 \times \exp\left(\frac{-PP_{Fitp} \times N}{sum_{Fit} + \varepsilon}\right)$$

$$B_2 = b_2 \times \exp\left(\left(\frac{PP_{Fitp} - |PP_{Fitk}|}{|PP_{Fitk} - PP_{Fitp}| + \varepsilon}\right) \times \left(\frac{PP_{Fitk} \times N}{sum_{Fit} + \varepsilon}\right)\right)$$

Table 1. Finest parameters of secondary controllers

Controller	Optimal values
TI	$K_{T1}^* = 0.6305, K_{I1}^* = 0.4415, n_1 = 3.065, K_{T2}^* = 0.6937, K_{I2}^* = 0.3942, n_2^* = 3.606$
TID	$K_{T1}^* = 0.6505, K_{I1}^* = 0.4216, K_{D1}^* = 0.2260, n_1 = 4.2205, K_{T2}^* = 0.6712, K_{I2}^* = 0.3030, K_{D2}^* = 0.2375, n_2^* = 4.3066$
TI-TID	$K_{T11}^* = 0.5350, K_{I11}^* = 0.3201, n_{11} = 3.0400, K_{T12}^* = 0.5637, K_{I12}^* = 0.2960, n_{12}^* = 3.0780, K_{T21}^* = 0.5370, K_{I21}^* = 0.3354, K_{D21}^* = 0.1460, n_{21} = 3.0470, K_{T22}^* = 0.5380, K_{I22}^* = 0.3290, K_{D22}^* = 0.1500, n_{22}^* = 2.9906$

Table 2. System dynamics comparison from Figure 3

Responses	Indices	TI-TID	TID	TI
ΔF_1	POs	0.00938	0.00982	0.01070
	PUs	0.02016	0.02215	0.02530
	ST	49.0560	55.0320	>100.00
ΔF_2	POs	0.00330	0.00462	0.00765
	PUs	0.01318	0.01570	0.01709
	ST	37.5500	44.3500	>100.00
ΔP_{tie12}	POs	0.00142	0.00160	0.00255
	PUs	0.00620	0.00770	0.00832
	ST	40.6302	50.5600	>100.00

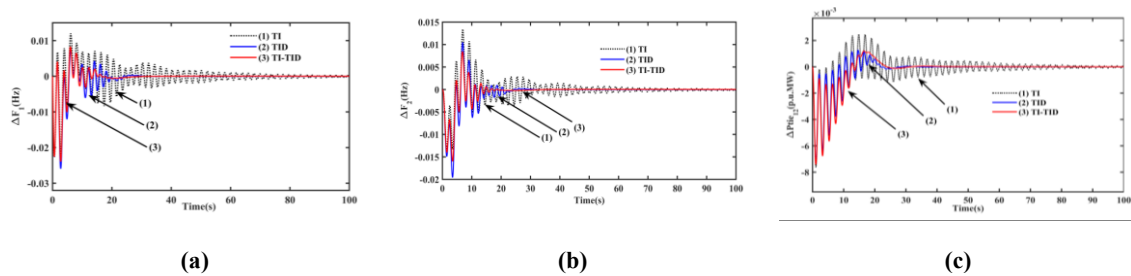


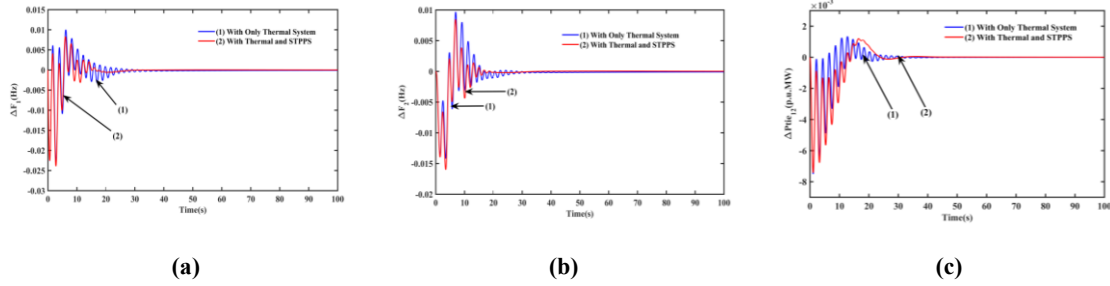
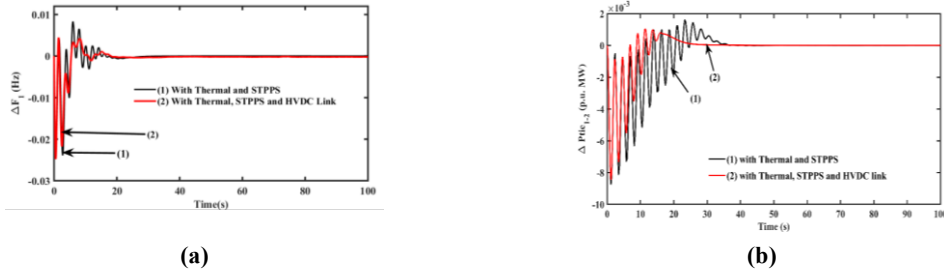
Figure 3. System dynamic response comparison for TI, TID, and TI-TID controller (a) ΔF_1 , (b) ΔF_2 , (c) ΔP_{tie12}

Table 3. Optimum TI-TID values considering STPPS

$K_{T11}^* = 0.5508$, $K_{I11}^* = 0.3502$, $n_{11} = 3.0410$, $K_{T12}^* = 0.5630$, $K_{I12}^* = 0.3004$, $n_{12}^* = 3.0600$,
$K_{T21}^* = 0.5206$, $K_{I21}^* = 0.3450$, $K_{D21}^* = 0.1670$, $n_{21} = 3.1480$, $K_{T22}^* = 0.5708$, $K_{I22}^* = 0.3470$,
$K_{D22}^* = 0.1706$, $n_{22}^* = 3.0069$

Table 4. Optimum TI-TID values considering STPPS

$K_{T11}^* = 0.5250$, $K_{I11}^* = 0.3325$, $n_{11} = 3.0750$, $K_{T12}^* = 0.5460$, $K_{I12}^* = 0.3073$, $n_{12}^* = 3.0577$,
$K_{T21}^* = 0.5195$, $K_{I21}^* = 0.3484$, $K_{D21}^* = 0.1709$, $n_{21} = 3.1904$, $K_{T22}^* = 0.5990$, $K_{I22}^* = 0.3500$,
$K_{D22}^* = 0.1801$, $n_{22}^* = 3.0190$

**Figure 4. Dynamics comparison with STPPS units (a) ΔF_1 , (b) ΔF_2 , (c) ΔP_{tie12}** **Figure 5. Performance with HVDC link Integration (a) ΔF_1 , (b) ΔP_{tie12}**

system that includes only the thermal unit, as in Figure 4. The outcomes indicate that the integration of STPPS in the projected system leads to enhanced dynamic performance.

Evaluation of HVDC integration

Study 5.3 explores the amalgamation of an HVDC into the system. The TI-TID values are enhanced using BSA, with the finest values presented in Table 4. The system dynamic performance, both with and without the HVDC link, is illustrated in Figure 5. The system with the HVDC link exhibits significantly better dynamic performance compared to the system without it.

Sensitivity analysis

To evaluate the durability of the top-performing TI-TID controller from Case Study-A, we consider two loading scenarios-25% and 75%-by varying the system load by $\pm 25\%$ from the

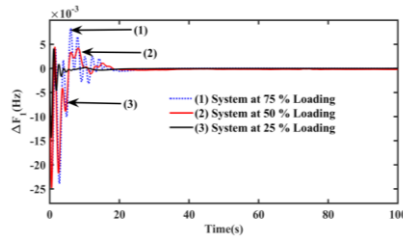
nominal 50% loading. After applying BSA, the optimal controller settings for each scenario are presented in Table 5. Figure 6 compares and illustrates the system dynamics for three load scenarios: 25%, 50%, and 75%. The TI-TID controller consistently maintains strong performance, even with load deviations of $\pm 25\%$ from the nominal value, as shown by the dynamic responses. This demonstrates that the TI-TID controller offers stable performance across various system loading conditions.

Impact of AVR on STPPS-Thermal system

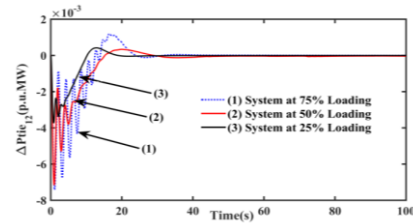
Figure 1(a) with STPPS-thermal is integrated with AVR and is under study. A thermal power plant, STPPS unit, and AVR loop are considered. BSA optimized the TI-TID gains, and its responses are plotted in Figure 7. The responses suggest the AVR loop outcomes over the AGC system by enhancing voltage and frequency stability.

Table 5. Control settings of TI-TID at varied loading

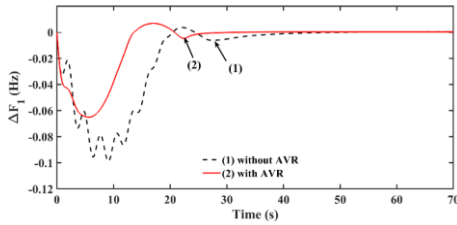
At 25 %	$K_{T11}^* = 0.5060, K_{I11}^* = 0.3005, n_{11} = 2.5402, K_{T12}^* = 0.49670, K_{I12}^* = 0.2538, n_{12}^* = 3.0001, K_{D12}^* = 0.3290, K_{T21}^* = 0.5002, K_{I21}^* = 0.3040, K_{D21}^* = 0.1230, n_{21} = 2.5405, K_{T22}^* = 0.4205, K_{I22}^* = 0.2975, K_{D22}^* = 0.1402, n_{22}^* = 2.0020$
At 75 %	$K_{T11}^* = 0.8205, K_{I11}^* = 0.4220, n_{11} = 4.0005, K_{T12}^* = 0.8216, K_{I12}^* = 0.3442, n_{12}^* = 4.0900, K_{D12}^* = 0.3290, K_{T21}^* = 0.8400, K_{I21}^* = 0.45010, K_{D21}^* = 0.3290, n_{21} = 4.5622, K_{T22}^* = 0.8251, K_{I22}^* = 0.3270, K_{D22}^* = 0.5510, n_{22}^* = 4.0860$



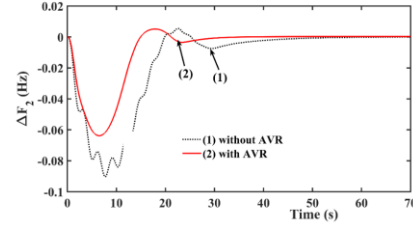
(a)



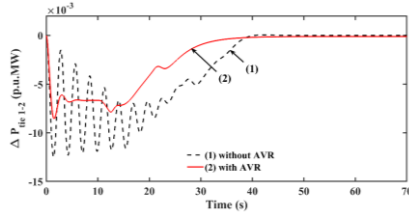
(b)

Figure 6. System performance at different loading (a) ΔF_1 , (b) ΔP_{tie-2} 

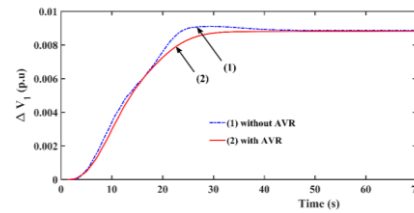
(a)



(b)



(c)



(d)

Figure 7. Impact of AVR (a) ΔF_1 , (b) ΔF_2 (c) ΔP_{tie-2} and (d) ΔV_1

Conclusions

An effort was made to improve the performance of a two-area AGC system by applying various secondary controllers, including TI-TID, TID, and TI controllers. The parameters of these controllers were enhanced using BSA. The results indicated that the TI-TID outperforms TI and TID controllers. The integration of STPPS improved the dynamics of the thermal system. Additionally, the inclusion of an HVDC further improved system performance. The sensitivity study confirmed that the TI-TID controller maintains stable performance across various system loading scenarios, eliminating the need to modify the original parameter values. Further, studies with AVR have shown significant

improvement in system dynamics. Furthermore, the proposed approach can also be extended to multi-area systems with varied renewables, broadening its applicability.

Appendix

- STPPS:** $K_{STPPS} = 1.0, T_{STPPS} = 11.50, T_{gstps}=0.08; T_{stps} = 0.3s, K_{stps} = 1.4.$
- Thermal System:** $F_i = 60\text{Hz}, B_i = 0.425\text{MW p.u}, H_i = 5.00 \text{ s}, T_{ij} = 0.0860 \text{ p.u.MW/rad.}, T_{gi} = 0.080s, K_{pi} = 120\text{Hz/pu}, R_i = 2.4\text{Hz/pu}, B_i = 0.425\text{MW/Hz}, T_{pi} = 20s, T_{ti} = 0.3s, K_{ri} = 0.5, T_{ri} = 10s,$
- HVDC:** $K_{HVDC} = 1.0, T_{HVDC} = 0.2s$

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