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Original Article

Hybrid Compensation based Load Frequency Control Using a Cascaded (1+PI)-PID Controller with TCSC and BES in Interconnected Power Systems

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Abstract - *In an electrical power system, the operating engineers are more concerned with keeping the frequency at the desirable value. If it deviates from the standard value, it will cause a reduction in operating life and efficiency of the component. This paper presents cascaded 1+PI with PID (1+PI)-PID optimized using the Kookaburra Optimization Algorithm (KOA) for Load Frequency Control (LFC) action, tested on a Two-Area Renewable Penetrated Multi-Source (TARPMS) power system. Nonlinearities are also imposed to model a real system with constraints. The cascaded controller performance is compared with PID using the honey badger algorithm, KOA, and WCA optimized fuzzy PID controller. Furthermore, the controller has also been examined on a Dual Area Thermal-Hydro system (DATH) well-analyzed in the contemporary work. The simulation results demonstrated the superior performance of the presented controller in settling down system deviations compared to the already stated control techniques. However, it is shown that nonlinearity constraints do affect the TARPMS system considerably, and they do need to be accounted. Moreover, it has also been analyzed when TCSC-BES devices have been coupled with the TARPMS system for supplementary control action, which gives more improvement to the system. Finally, robustness analysis is carried out on the TARMPS secondary and supplementary control level.*

Keywords - *Power system stability, (1+PI)-PID controller, KOA technique, TCSC-BES strategy, Robustness Analysis.*

1. Introduction

1.1. General

Unprecedentable and ever-changing conditions in power generation, transmission, and usage impose considerable problems before contemporary Interconnected Power Systems (IPS). The increasing presence of Renewable Energy Sources (RES) leads to substantial uncertainties and an intermittent nature to the system, which makes the problem of load balancing and frequency regulation more complex.

One of the main functions to meet equal conditions between the powers demanded and generated in a grid system is the Load Frequency Control (LFC). As far as it concerns about the security and reliability of the entire energy network, then dynamic stability is of prime importance for modern power networks. The varying and unpredictable nature of the load demands is one of the critical tasks that has been looked into for the interconnected networks. The generator and the demand side powers need to be equal, which has to be done without fail, and, in case of large or rapid load disturbances, it has to be done with utmost care [1].

1.2. Literature Survey

From the perspective of modern power systems, studies on Multi-Area LFC have developed to address the growing complexity in operational stability and robustness of the power system. The development of these control strategies, from simple PI controllers to complex model predictive control, has kept pace with the increasing dynamics of power generation and network operation, alongside the need for adaptive, efficient, and robust controllers under ever-growing power demand, increased integration of renewable resources, and modification of power grid infrastructure. For over several decades, Multi-Area LFC has developed with other power system technology and theory in parallel. A PI/PID-based controller-based mechanism was applied to a two-area multi-source system in [2], which handled the Honey-Badger Algorithm (HBA) optimization technique. The HBA's supremacy in locating the optimal controller parametric to handle the IPS functional stable is compared with the proven methodologies of Particle Swarm Optimizer (PSO), Spider Walrus Algorithm (SWA), and Grey Wolf Optimization (GWO). A PID derived with PSO strategy and an amalgamated Genetic-Algorithm (GA) is implemented for isolated [3] and connected thermal systems. However, the modeled thermal system is a non-reheat one, and the technical non-linearities of Generation-Rate-Constraints (GRC), Governor-Dead-Band (GBD) were neglected. A comparative study on PI/PID for a two-area IPS having gas, hydro, and wind is described in [4] for a simulated model. Separate tuning strategies such as the Integral rule, Ziegler-Nichols tuning, PSO, and Teaching-Learning optimizer mechanism were individually enforced to obtain optimum parameters of controllers. This research analysis confirmed the supremacy of teaching-learning-based PIDF over the control mechanism, but the analysis did not involve constraints of reality. [5] describes a typical Interconnected Power System (IPS) that includes thermal generation units and applies an ARO algorithm based PID control method. To illustrate the capability of the presented controller, its performance is compared to differential searching, JAYA, PSO, and SAMPE-JAYA algorithms. Soft computing algorithms are widely used to tune classical PI/PID controllers, and they offer satisfactory performance and the applicability to determine optimal parameters for linear system models. However, a real practical system does not contain any linear model, and therefore using PI/PID control strategies only is not capable to achieve the frequency stability.

From the above, in recent years, because of better robustness and adaptability, the research has shifted from classical PI/PID control schemes to the intelligence and multiple degrees of freedom controllers. Now, the Fuzzy Logic Control (FLC), the regulators designed by the Degree-of-Freedom (DOF) theory of Fractional Order (FO) calculus, and their cascade connections are becoming popular. An optimal fuzzy PID controller for regulating variations in an interconnected network was designed by enacting the Water Cycle Algorithm (WCA) by the authors in [6]. Moreover, the GRC-GDB were studied, and IPS was modelled with Communication Time Delays (CTDs). The performance dominance over the PI/PID and 2DOFPID controllers has been evaluated. Researchers had proposed and tested different intelligent controllers, and comparative analysis indicates the advantage of the FOPID-FOID [7] method in dynamic behavior when facing with load disturbance.

For improving multi-microgrid system stability, the cheetah optimization algorithm-aided FOPID [8] has been proposed. Analysis has proved the proposed method is outstanding against PID and exhibits robust performance by enhancing the settling time and minimizing the under/overshoots. For the Ethiopian IPS, the authors [9] enforced the Artificial Neural-Network (ANN) regulator trained in iterative methodology, and the researchers confirmed the dominance of the iterative trained ANN over PID. In [10], the researchers recommended the zebra optimizer tuned Tilt-Integral-Derivative (TID) for renewable integrated IPS, and the recommended regulator supremacy is validated with well-established methodologies like PI/PID & TI/TID controllers and is justified through performance comparison.

In [11], TLBO tuned fuzzy PID controller for frequency regulation has been applied on a two-area IPS (composed of hydrothermal and nuclear generation units). It compared the performance of TLBO tuned fuzzy PID controller with PO tuned PI, DE-tuned PID, TLBO tuned PID controllers. The study has also been enhanced for EV penetration along with an IPFC-SMES control strategy. In [12], differential-evolution tuned 2DOF-PID is applied on a thermal dual-area system, and time domain indices have also been compared. The performance of WCA-tuned 3DOF-PID, along with PID and 2DOF-PID, has also been reported in [13] for non-linear dual area IPS. Several other advanced controllers based on optimum tuning have also been applied on different types of IPSs, including Non-dominated GA based FOPID [14], PI-(1+FOPID) with wild horse methodology [15], Slap swarm algorithm tuned FOTID [16], FOPID-TID [17], FOPID-(1+TD) [18] tuned with squirrel search and flow-direction techniques, 1+PD-PI using mountain gazelle technique [19], FOI-FOPID using squid game optimizer, FOPI-1+TD using flow direction technique, etc. Apart from the controller design, the researchers had selected different optimizations over the years to find suitable parameters for the controller to perform better.

After referring [22], it is came to know that the algorithms of sand-cat algorithm, mayfly algorithm, mango optimizer, black widow technique, coati optimization, dandelion algorithm, stochastic diffusion search, reptile search algorithm, osprey optimization, puzzle optimization technique, goat optimization, Kepler methodology, sea-horse optimizer, heap-based optimization, simulated annealing, diligent cow search technique, back tracking algorithm, flora optimization, electro search technique, tuna swarm algorithm, wind driven optimizer, electro-magnetic optimization, spotted hyena approach, ray optimizer, falcon optimization, coyote algorithm, artificial eco-system optimizer, bacterial foraging and bull lion algorithm, bidirectional butterfly approach, reptile search technique, krill herding algorithm, chameleon optimization, metal annealing, pigeon inspired optimization, chimp algorithm, northern goshawk optimization, monkey search technique, social emotional optimization, jellyfish optimization, lion optimizer, human inspired algorithm, weightless warm optimization, skill optimizer, intelligent water drop, tunicate search algorithm,. central force optimization, and the African vulture approach, etc., are utilized, and there is still scope for the new algorithms to serve in the domain of LFC. To clearly identify the research gap, a critical literature survey is conducted on the most recently published literature that has concentrated on PI/PID-aided control approaches, as made available in Table 1. After a comprehensive literature survey on the newly research papers, it has been realized that many evaluation models or IPS networks are mentioned in LFC research. Moreover, it has been understood that the technical constraints are not been concerned with the non-linearity constraints in the researches [2, 3, 5, 8, 10, 16, 18, 20, 21]; the effects of GRC-GDB are concerned with the researches [4, 7, 11, 12, 13, 14, 15, 17, 19]; and the effects of GRC-GDB-CTDs are concerned with the researches [6, 12]. Thus, it has been found that there are no researches which has considered the non-linearity constraints of every type in the LFC studies and might have an effect on controllers at a large-scale IPS network. So, it motivates the authors of this study to consider the IPS model with the GRC-GDB-CTDs and show the resulting impact.

1.3. Problem Identification and Research Motivation

Many traditional controllers have complex control strategies or poor dynamic response in diverse operating scenarios. Additionally, they possess several tuning parameters that need adjustment [22]. As a result, this work attempts to design a controller to eliminate these limitations while simultaneously ameliorating the performance and enhancing the results over traditional techniques. The increased complexity of modern IPSs that have a high capacity of RES integrated, along with the constantly changing load conditions, has exacerbated the effort needed to sustain system frequency. Conventional PI/PID controllers often do not demonstrate great adaptability under dynamic, nonlinear, and time-varying system conditions, causing worse dynamics and oscillations. To this end, this proposed control scheme is a cascaded (1+PI)-PID type structure for robust frequency control. It uses the fast dynamic error response of an inner (1+PI) loop with the accuracy of the damping characteristic by the outer PID loop, which consequently provides improved transient and steady state response under load disturbances. In addition, the cascade structure leads to enhanced frequency regulation during different load dynamics, especially at conditions where nonlinearities appear within the system. In this case, the coordinated effect of primary and secondary controller action ensures the frequency is near its nominal value, yielding a faster response. Thus, the cascade (1+PI)-PID control scheme proves to be a robust and reliable method for dynamic stability of frequency.

Table 1. Critical literature survey

Reference	Year	Test System	Controller	Optimization algorithm	Major Concentration	Limitations
[23]	2025	Isolated system	PID	Geometric mean optimizer	Dampening of deviations	Ignored the practicality constraints
[24]	2024	Two areas with wind penetrated system	PID	Aquila optimization	Reduction of settling time	Linearized model
[25]	2024	Two area traditional system	PI-PID	PSO-GWO	Enhanced overshoots and settling time	Renewable penetration is not considered
[26]	2024	Wind integrated two area IPS	PID	PSO- Artificial Hummingbird Algorithm (PSO-AHA)	Reduced dampening and overall stability	Ignored the practicality constraints
[27]	2025	Two-area hydrothermal model	PID	GWO	Focused on enhanced stability	Though deliberating the GRC, its effect is not explored.
[28]	2025	Two-area non-linear thermal unit	PID with ANN	Cat-pikas optimization	Overshoot reduction and improved settling time	Computational complexity and the realistic constraint dominance are not explored.
[29]	2025	Isolated model	PI-(1+DF)	Fick's law-based optimization	Robust stability performance	Analysed the linearized system
[30]	2024	Multi-area multi-type system	PID	Lyrebird optimization	Reduced settling time	Not explored the CTD's effect
[31]	2024	Multi-area model	Robust PID	Frequency loop shaping	Overall system efficiency	Not explored the CTD's effect

The system integrated with TCSC and BES in a coordination scheme under (1+PI)-PID is used to more effectively improvised proposed scheme on frequency regulation. Rapid varying of line reactance can increase power flow controllability, enhance system damping by TCSC, and provide an instantaneous active power support to load fluctuation by BES. As a consequence of its coordination mechanisms with the controller and between TCSC and BES, which is not often presented on literature, an effective power transfer is confirmed among different areas.

The major highlights are listed below:

- Cascade (1+PI)-PID as a regulator for frequency stability is assessed.
- KOA is enforced to locate the (1+PI)-PID parameters for performance suitability.

- Performance of the proposed control technique is demonstrated, and the dominance is validated by testing on the DATH and TARPMS systems over established control methodologies reported recently.
- The effect of CTDs and GRC-GDB on performance and resilience is illustrated.
- TCSC-BES is used as a territorial strategy, and stability improvement is assured.

2. Dynamic Model of the Power System

The two models that were discussed in this paper are the DATH and TARPMS power systems to test the suitability of (1+PI)-PID as a frequency regulator. The models considered are displayed in Figure 1 and Figure 2, and the stability examination was tested against the area-1 and the SLP of 10%. The two areas are characterized by each area having its own thermal-hydro units in the DATH model, and for the TARPMS system, two areas each having both hydrothermal units [32] and a wind energy conversion plant. Model the thermal plant possessing GDB of 0.036Hz and GRC of 3%/min for increasing generation and 5%/min for decreasing generation. Model the hydro plant having a GRC of 2.5% per min while increasing generation and 3.3% per min for decreasing generation. Further, it is known that the IPS covers an extensive network and is operated through communication peripherals for effective communication of data and control signals between geographically diverse locations. An example is when data from remotely installed terminal units is relayed to the control centre via peripheral elements, where it can be processed to devise control signals which are then relayed back to the secondary controller within the plant premises through similar peripheral elements, which are used to displace the operational point of the system such that frequency deviations are minimized. The communication peripherals cannot perform this process in an instant, and a latency is observed due to the inherent delay, which is referred to as CTDs, which would have a destabilizing effect on the power system. In this paper, the model for CTDs considered in TARPMS is presented in Equation (1), with 'Ʈd' representing the time delay. 0.25 seconds is taken as a time delay as per [33].

$$e^{-s\tau_d} = \frac{1-\frac{\tau_d}{2}s}{1+\frac{\tau_d}{2}s} \tag{1}$$

The parameters Ptie is the tie-line error, ΔPD is load deviation, and Δf1 is the frequency deviation in area1, and Δf2 is the frequency deviation in area2. The variables required to design DATH and TARPMS in MATLAB/SIMULINK are available in the literature [24, 32].

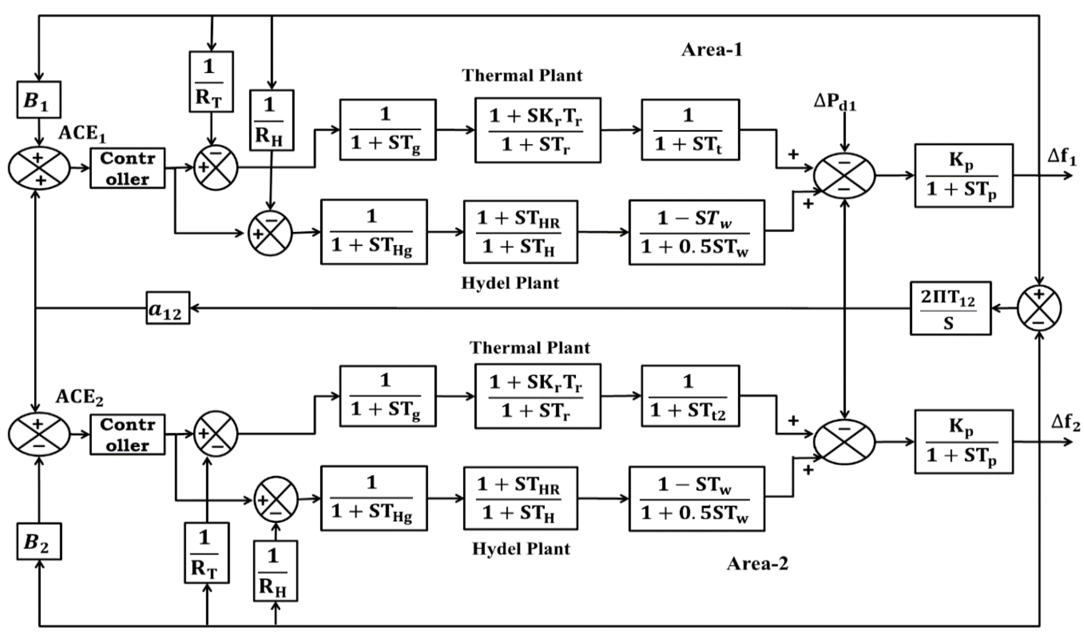


Fig. 1 Model of the DATH system under dynamical study

3. Objective Function and Proposed Controller

The cascade (1+PI)-PID is a multi-loop control system that utilizes the benefit of the feedback path to achieve enhanced performance within nonlinear systems that are found in interconnected power systems based on renewable sources. It essentially involves two controller loops: an outer and an inner loop. It is also the duty of the external loop to ensure the functioning of the system is stable, whereas the inner loop, being a 1+PI controller, serves to ameliorate the transient behaviour. Figure 3 depicts that the (1+PI)-PID structure can be seen to be the proportional term, which has unity gain, and the PI action can be expressed by Equation (1), and the PID can be expressed by Equation (2).

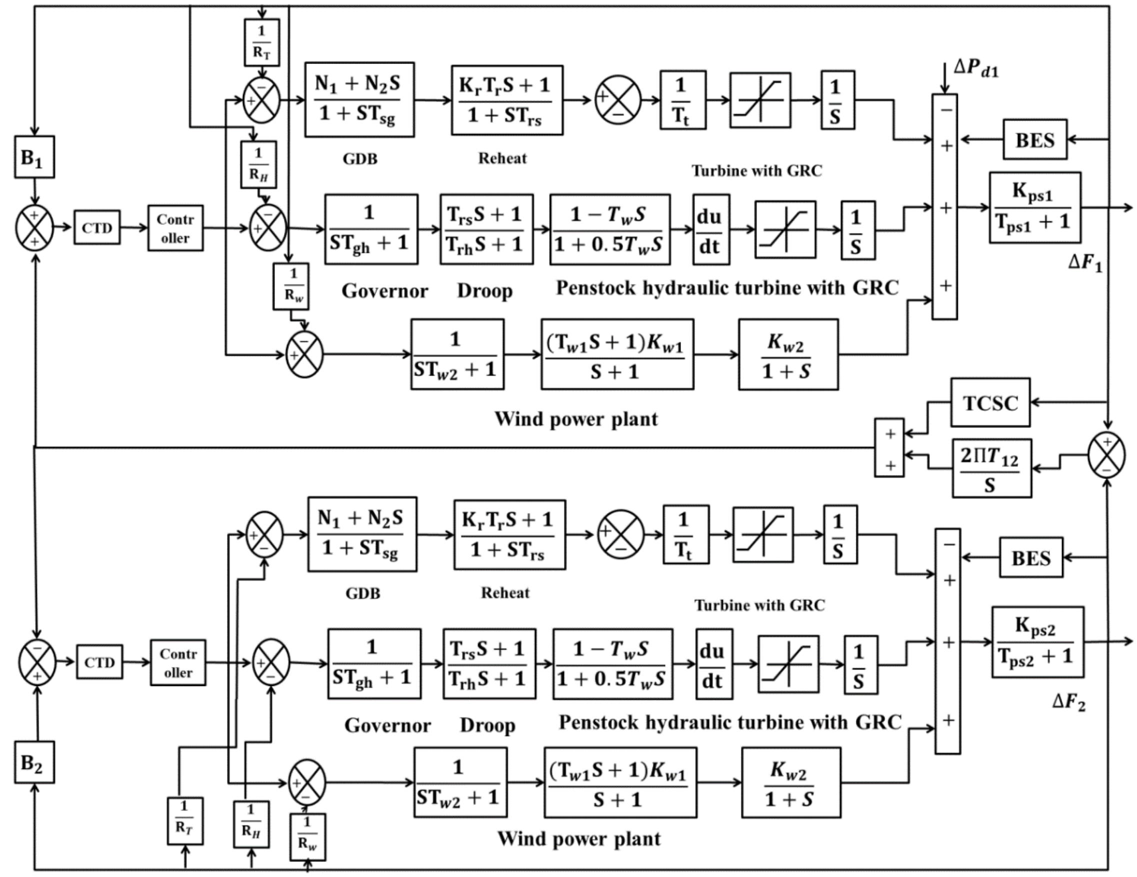


Fig. 2 Model of TARPMS power system for dynamic study

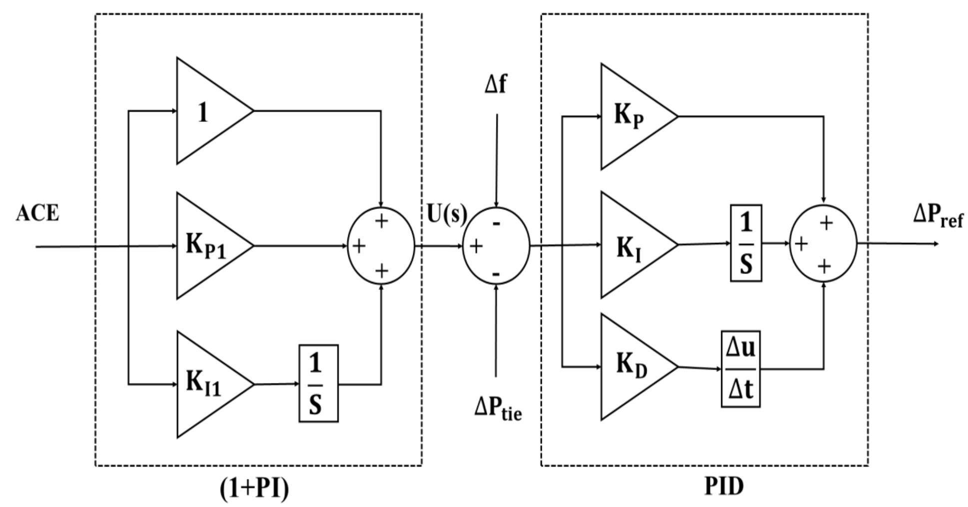


Fig. 3 Configuration of Cascade (1+PI)-PID Controller

$$G_{(1+\mathrm{PI})}(s) = 1 + K_{\mathrm{p1}} + \frac{K_{\mathrm{i1}}}{s} \quad (1)$$

$$G_{\mathrm{PID}}(s) = K_p + \frac{K_i}{s} + sK_d \quad (2)$$

In a cascade structure, the outer controller (1+PI) takes charge of system error, generates a reference for the inner PID controller, and this PID operates in high sampling frequency to make good disturbance rejection and tracing an intermediate reference, and the two loops coordinate each other in an optimum transient and steady-state response simultaneously. This two-loop cascade system is suitable for cascaded control, which controls the high-frequency response in the inner loop and low-frequency dynamics in the outer loop, and this two-loop system could effectively realize decoupled control purposes. In order for the LFC actions to be carried out efficiently, the (1+PI)-PID is designed appropriately as a regulator. There are 5 parameters to be tuning for the controller, and the KOA method is applied to reduce the value of the ISE index in Equation (3).

$$J_{\mathrm{ISE}} = \int_0^{T_{\mathrm{Sim}}} \left(\Delta \mathrm{f}_1^2 + \Delta \mathrm{P}_{\mathrm{tie12}}^2 + \Delta \mathrm{f}_2^2\right) .\mathrm{dt} \tag{3}$$

4. Proposed Kookaburra Optimization Technique

A carnivorous bird native to Australia and New Guinea, the Kookaburra is in fact a group of terrestrial tree kingfishers and belongs to the genus. The habitat of the Kookaburra varies from arid savannahs to tropical wet forests to suburban areas where trees grow sufficiently tall. The calling bird is known by the unique call that sounds like human laughter and is used by the bird to mark territory and deter trespassers. The Kookaburra is typically about 28-47 cm long and weights 300g on average. It has a body covered in blue, brown, and white feathers with a prominent dark stripe found behind the eye. The Kookaburra's feeding behavior involves a rapid dive down onto a live creature – insect, small reptile, or rodent – followed by often beating it against a branch until dead and then devouring it. This method of predation, which can be viewed as smart and efficient in its way, inspired the idea of the Kookaburra Optimization Algorithm (KOA) [34].

It is a population-based approach and can demonstrate a possible way to solve the optimization problem through an iterative procedure. The population of KOA is a population of kookaburras, which are sparse in searching the domain randomly, initially as described in Equation (4).

$$X_i^0 = X_{\min} + \mathrm{rand}(0,1).(x_{\max} - x_{\min}) \tag{4}$$

In which X0i position of the ith bird in the zeroth iteration, and xmax and xmin indicate the searching limits. Then the objective function f is defined as:

$$f_i = f(X_i^{t+1}) \tag{5}$$

Subsequently, the prey and its kill operations are performed; they are analogous to the exploration and exploitation parts of the algorithm. Proximity D between the prey and the Kookaburra is calculated using the position Xbest of the Kookaburra as defined in Equation (6). The optimum solution for the problem (minimization type) is determined based on the position that corresponds to the minimum objective function value of the Kookaburra; the subsequent update to the Kookaburra positions is as in Equation (7).

$$D_i = |X_{\mathrm{Best}} - X_i| \tag{6}$$

$$X_i^{t+1} = X_{\mathrm{Best}} + A.D_i.\mathrm{Cos}(\mathrm{rand}(0,1) \times 2\pi)` \tag{7}$$

The above process will be carried out until the maximum iterations are achieved. This algorithm is applied separately in the .m file using MATLAB version 2022a, where the total number of populations and iterations is defined as 50.

5. Coordinated TCSC-BES Strategy

Dynamic stability improvement is only feasible with an adaptive and regionally coordinated control for nonlinear IPS. This paper presented a coordinated control with TCSC and BES to improve the system response. Figure 4 illustrates the location of the coordinated TCSC-BES control in the TARPMS system.

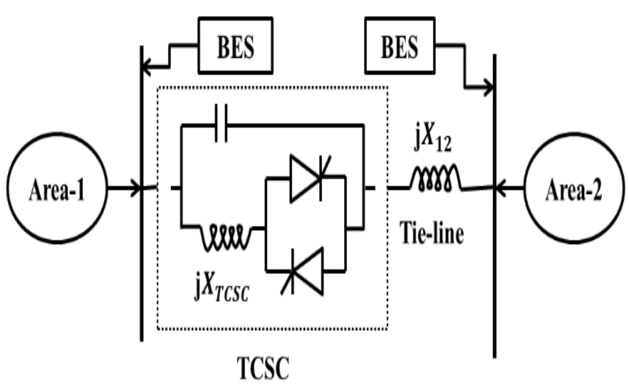


Fig. 4 A single line representation of IPS with TCSC and BES

5.1. Damping Control Scheme of Thyristor-Controlled Series Compensator

TCSC is one among the series FACTS and is the Thyristor-based control variable parameter line adjustment technique. TCSC is composed of a fixed capacitor and a TCR in parallel to make a variable impedance [26]. The TCSC allows effective line reactance to be adjusted smoothly in accordance with the system conditions. In addition to compensation of impedance, TCSC has many benefits in controlling power flow, enhancing voltage stability, damping oscillations, reducing line losses, improving power transfer capability, and so on. The control structure for the TCSC damping control scheme is shown in Figure 5. Power change of the tie-line (P tie12) can be defined with respect to the TCSC parallel with the tie-line by Equation (8).

$$\Delta P_{tie12}(s) = \Delta P^0_{tie12}(s) + \Delta P_{TCSC}(s) \tag{8}$$

Where, ΔP0tie12 and ΔPTCSC represent the tie-line power without TCSC and the power flow effect through TCSC. In addition, the expression of ΔPTCSC is given in Equation (9), and the compensation factor is ΔKc, which could be written as Equation (10).

$$\Delta P_{TCSC} = \Delta K_c + \Delta K_c^2 + \Delta K_c^3 .... \tag{9}$$

$$\Delta K_c(s) = \frac{K_{TCSC}}{1+sT_{TCSC}}\left(\frac{1+sT_1}{1+sT_2}\right).\left(\frac{1+sT_3}{1+sT_4}\right).\Delta Error(s) \tag{10}$$

The time and gains of TCSC are TTCSC and KTCSC, and time lag-lead indicators are T1, T2, T3, and T4. The parameters value which will be discussed and considered here have recently been mentioned at [35].

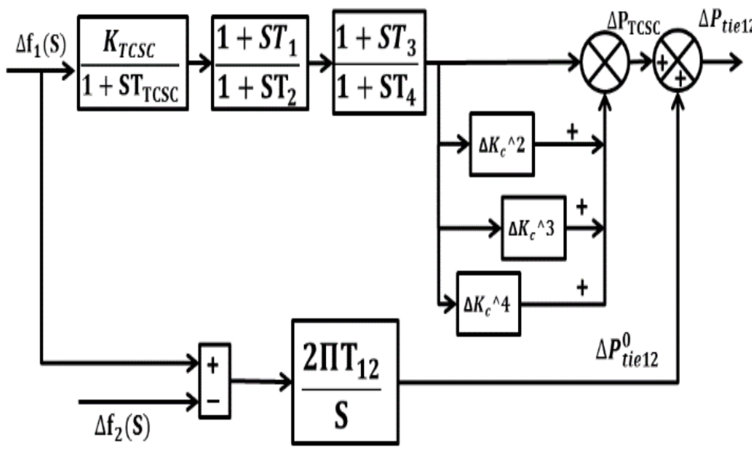


Fig. 5 TCSC as a damping controller

5.2. Battery Energy Storage

High penetration level of renewables, like wind and solar energy, in the existing power system has led to frequent and erratic variations in the power system. The randomness of fluctuations imposes constraint to frequency regulation and the dynamic stability mechanism.

The BESS is among the crucial ancillary components that contribute stability, flexibility, and robustness. In an interconnected system, system frequency will be used as a direct indication to determine the balance between supply and demand of power.

BES will act as an instantaneous storage component to inject or absorb active power on a millisecond time scale. With increasing load causing the system frequency drops, the BES injects the required additional power instantaneously, and in contrast, when supply overloads and the system frequency goes up, the BES absorbs the extra energy and do not allow the frequency to go over the frequency value.

BES will thus be a very appropriate component for primary and secondary frequency regulation. The parameters of BESS implemented in this work, represented by Equation (11) [36], KBES, and TBES are set to 0.835 and 0.979 seconds.

$$G_{BES}(s) = \frac{K_{BES}}{1+sT_{BES}} \tag{11}$$

6. Simulation Outcomes

6.1. Scenario-I: Analysis of DATH System with Several Control Approaches

The prominent system DATH from the survey of literature is taken up for the investigative study by infusing a Step Load Perturbation (SLP) 10% in area-1, to analyze the performance of KOA tuned (1+PI)-PID in comparison with other control techniques. For this, the recently reported control approaches of AO-tuned FOPID [24], PSO-AHA tuned PID [26], and GWO tuned PID [27] are tested on the DATH system along with the proposed controller, and the responses are under the comparison in Figure 6. The settling times of DATH system responses that are obtained under various control schemes are in Table 2. From Figure 6 and Table 2, it is clear that the KOA-enabled (1+PI)-PID is effective in dealing with the enhancement in settling time. Moreover, the reduction of peak undershoots is also observed, and it is noticed to be 0.036Hz, 0.029Hz, 0.018Hz, and 0.016Hz in the sequence of GWO, PSO-AHA tuned PID, AO enabled FOPID, and KOA enabled (1+PI)-PID for Δf1. For Δf2, these are identified to be 0.0087Hz, 0.0076Hz, 0.0063Hz, and 0.002Hz in the above control sequence, and for ΔPtie12, it is recorded as 0.0061pu, 0.0039pu, 0.002pu, and 0.0017pu. The two control loops in the proposed controller are handy enough in rejecting the disturbances effectively, and the robustness of the KOA algorithm in obtaining the optimal controller parameters. These features made the proposed control approach effective in dealing with the IPS stability under SLP.

Table 2. DATH system responses settling time

Settling time (Seconds)	PID:GWO	PID:PSO-AHA	FOPID:AO	Cascade(1+PI)-PID: KOA
Δf_1	7.96	5.45	4.38	3.61
ΔP_{tie12}	8.35	6.54	4.83	3.78
Δf_2	8.21	6.22	4.47	3.22

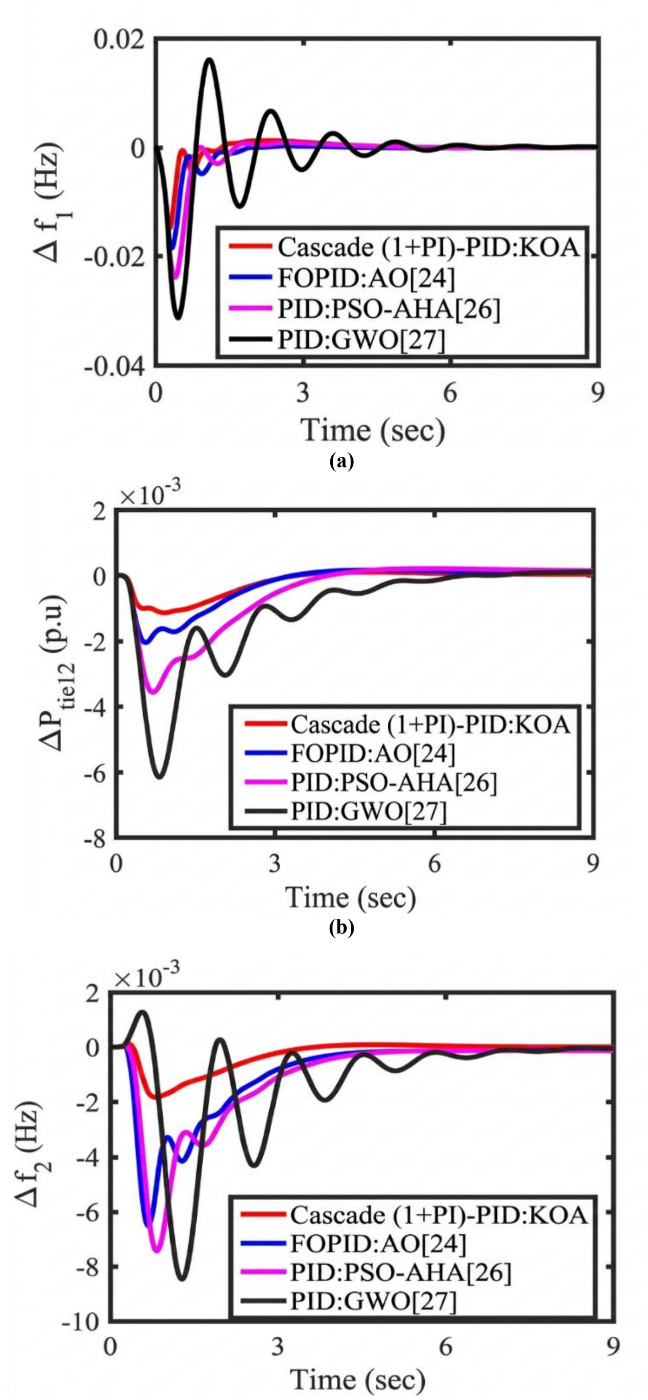


Fig. 6 Responses for scenario-I, (a) ∆f1 (b) ∆Ptie12, (c) ∆f2.

6.2. Scenario-II: Analysis of the TARPMS System with Several Control Approaches

In this subsection, a comparative review has been attempted on the TARPMS system being operated with different control schemes independently.

The control structures include the PID driven by HBA, PID driven by KOA, fuzzy PID driven by WCA, and the proposed KOA-driven (1+PI)-PID for injecting 10%SLP in the first control region. Besides this, the GRC-GDB and CTD constraints are imparted. The behavior of the TARPMS system with the aforementioned governing actions is showcased in Figure 7 for identifying the best control technique.

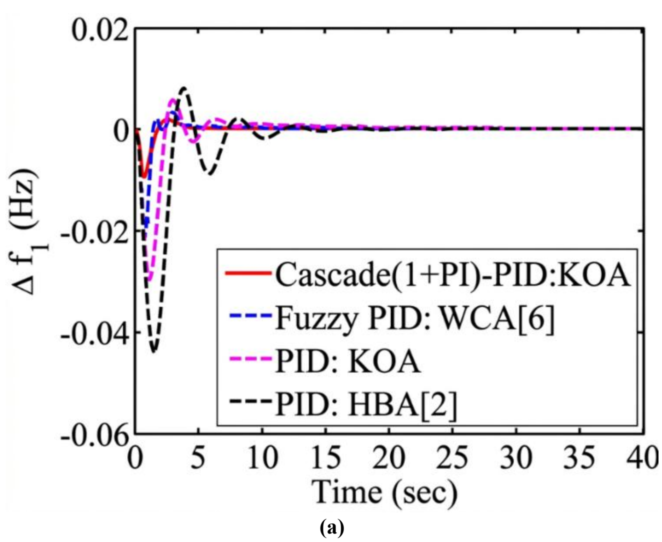
The settling time of each response in seconds is read from the Figure 7 and noted in Table 3. From Table 3 and the dynamic response shown in Figure 7, it can be noticed that the introduced regulator effectively brought back the deviations of the responses to zero-state position within a very short span. Beside this, the peak undershoots corresponding to the f1 under the PID driven by HBA, PID driven by KOA, fuzzy PID driven by WCA and the KOA driven (1+PI)-PID are calculated and represented as 0.039Hz, 0.028Hz, 0.021Hz and 0.007Hz, peak undershoot for f2 are computed as 0.0038Hz, 0.003Hz, 0.0024Hz and 0.0019Hz, and peak undershoot for Ptie12 are computed as 0.038pu, 0.023pu, 0.015pu and 0.0035pu for each of PID driven by HBA, PID driven by KOA, fuzzy PID driven by WCA and the proposed KOA driven (1+PI)-PID, respectively. It can be clearly noticed that the peak undershoot of all the responses is greatly damped. Besides, the objective function ISE value is also significantly improved by 90.87%, 75.01%, and 67.49% with PID driven by HBA, PID driven by KOA, and fuzzy PID driven by WCA, respectively. The gains for the above controllers in Table 4. Figure 8 compares the convergence speed of different control strategies used in this paper, and it can be observed that the designed regulator structure, as well as the algorithm, quickly and smoothly reached the optimum point. The significance result from the analysis made is that the proposed KOA enabled (1+PI)-PID performs significantly well when compared to other conventional controllers applied.

Table 3. TARPMS responses settling time

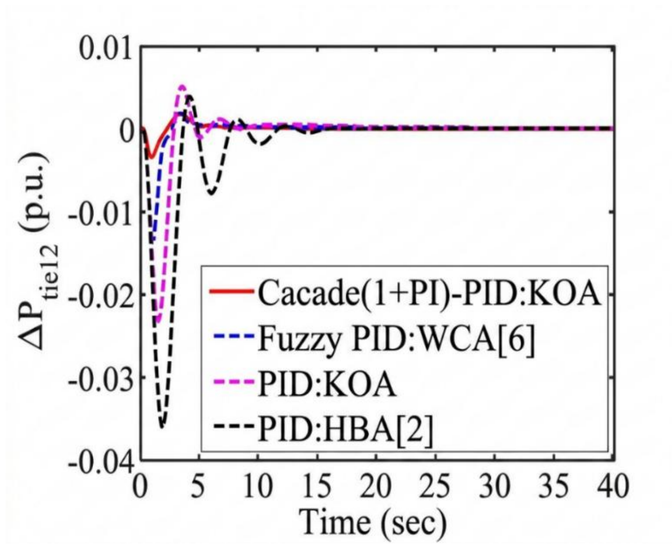
Settling Time (Seconds)	Δf_1	ΔP_{tie12}	Δf_2	ISE*10^{-3}
HBA: PID	17.83	17.189	21.841	13.295
KOA: PID	12.139	15.069	17.86	4.85
WCA: Fuzzy PID	7.87	10.641	11.012	3.731
KOA: (1+PI)-PID	5.786	6.75	7.23	1.212

Table 4. Controller optimal parameters

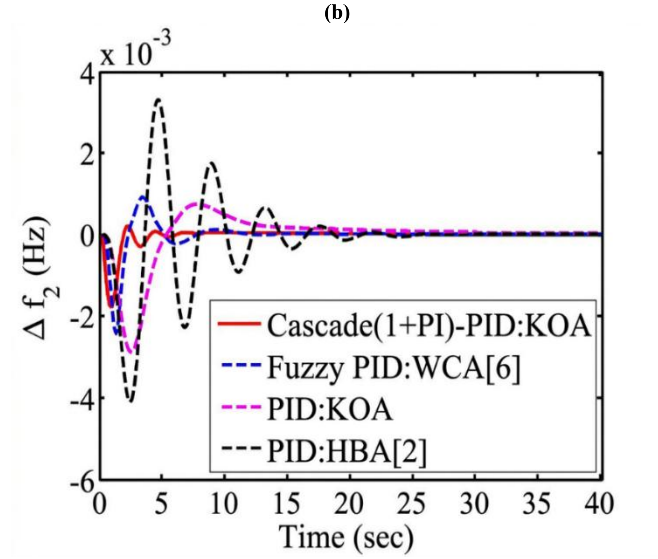
Controller		K_P	K_I	K_D	K_{P1}	K_{I1}
Area-1	HBA: PID	1.440	0.667	0.348	-	-
	KOA:PID	1.176	0.381	0.515	-	-
	WCA: Fuzzy PID	1.399	0.182	0.683	-	-
	KOA: (1+PI)-PID	1.127	0.508	0.276	0.136	0.142
Area-2	HBA: PID	1.642	1.085	1.332	-	-
	KOA:PID	1.319	0.523	1.051	-	-
	WCA: Fuzzy PID	1.593	0.522	0.381	-	-
	KOA: (1+PI)-PID	1.412	0.389	0.786	0.206	0.224



(a)



(b)



(c)

Fig. 7 Responses for scenario-II, (a) ∆f1, (b) ∆Ptie12, (c) ∆f2.

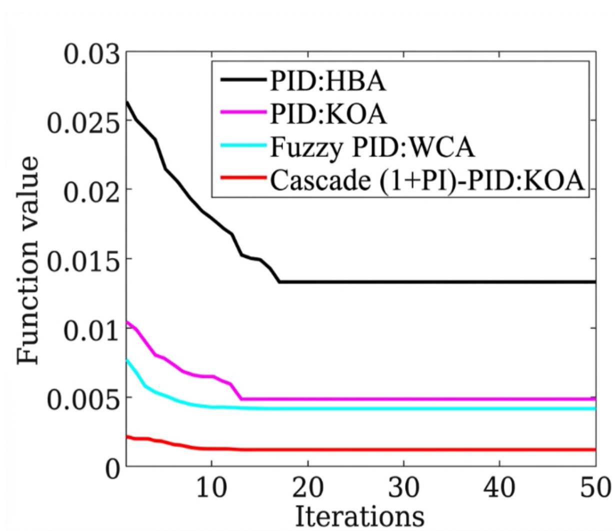
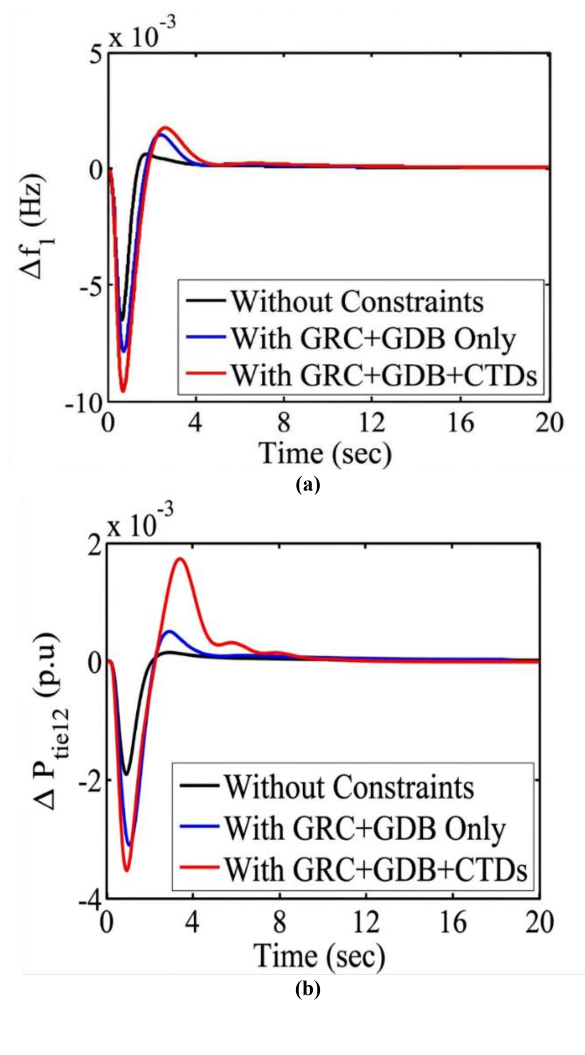


Fig. 8 Convergence characteristics

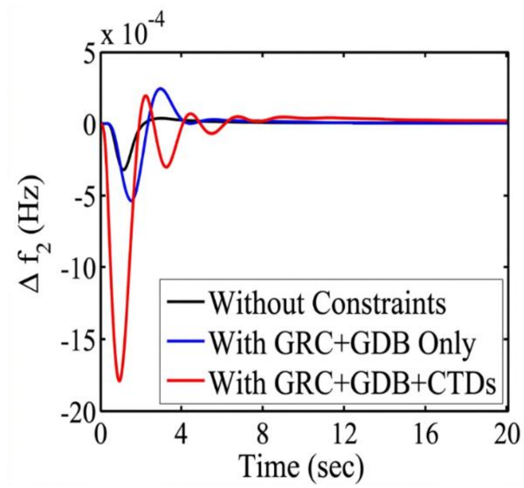
6.3. Scenario-III: Effect of Practical Nonlinear Constraints on TARPMS Dynamic Performance

This analysis has been done in order to present the influence of non-linearity constraints that were used in the proposed study model. This kind of investigation should be done in order to determine stability analysis under some close conditions, with that of an actual real-time system. For this reason, a separate analysis on the TARPMS power system, which was regulated by KOA, enabled (1+PI)-PID to be performed. This is based on the fact that it exhibits better performance compared to the other techniques.

The analysis was conducted in three different cases: (1) ignoring the GRC-GDB and CTDs effect, (2) considering the GRC-GDB effect and ignoring the CTDs effect, and (3) considering both the GRC-GDB and CTDs effect. To elucidate these effects clearly, these three responses were superimposed on a single plot (Figure 9). From Figure 9, it can be clearly noted that the deviations in the system's response when all types of non-linearity constraints were neglected were small, and there was a slight increase in the deviation of response when only the GRC-GDB was considered. When GRC-GDB was considered, it was found that the system was unable to react to the frequency fluctuations within the specified range and therefore, there was a noticeable deviation in system response. And when both GRC-GDB-CTDs were incepted, the deviation was considerably larger, and hence it can be established that the CTDs are indeed playing a significant role. The addition of CTDs in the control system introduces a delay in control signal formation, and also a delay in the delivery of the same to the appropriate location. So, the speed of variation of the operating point of the power system is quite large. As a result, the delay of varying the operating point causes a large deviation in real power unbalance and system response. Hence, it is proposed that while developing the secondary controller, non-linearity constraints need to be incorporated to analyze the stability of the IPS under the most realistic operating conditions. Ignoring the constraints may result in the design and implementation of an inappropriate controller that could destabilize the IPS upon the emergence of unexpected time delays within the system. It is a population-based approach that can propose a solution for the optimization problems in an iterative fashion. The population consists of kookaburras that are dispersed randomly in the search space at the beginning.



(b)

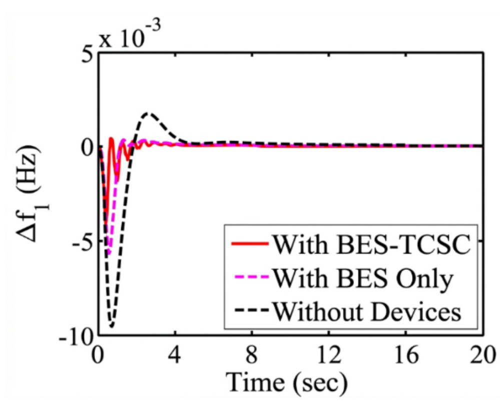


(c)

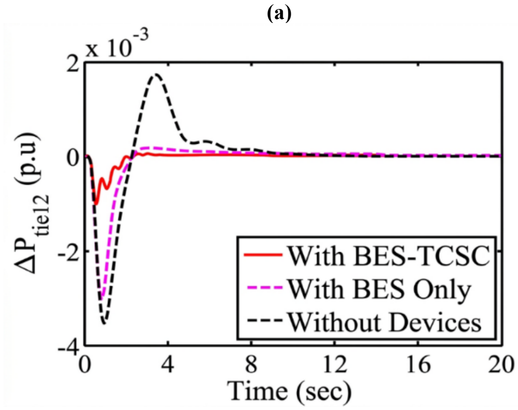
Fig. 9 Scenario-III responses, (a) ∆f1, (b) ∆Ptie12, (c) ∆f2.

6.4. Scenario-IV: Dynamic Performance Analysis of TARPMS Using KOA-Based Cascade (1+PI)-PID Controller integrated with TCSC-BES Integration

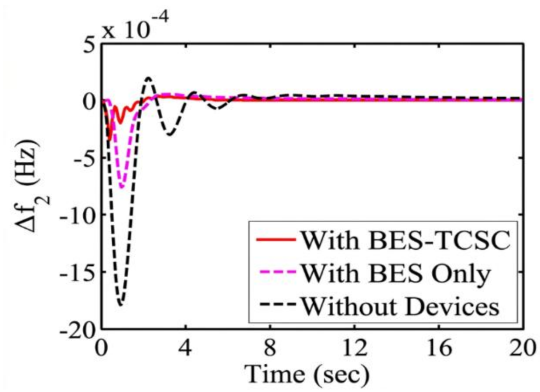
In order to get away from these extra fluctuations appearing in the dynamic behavior of the TARPMS power system with non-linearity constraints, either the territory or supplementary control technique is employed. This paper exploits the dominant TCSC-BES strategy to handle the extra deviations in the KOA-tuned cascade (1+PI)-PID controller-based secondary control. At the beginning, BES is connected with areas 1 and 2, and the response is shown in Figure 10. Afterward, by keeping BES active in the areas, TCSC is placed in the tie-line, as Figure 10 deliberates the responses. The incorporation of BES has improved the performance of the system, and further enhancement is observed when the BES-TCSC coordinative approach is employed.It is stated that the required settling time is in Table 5, and obviously, the responses achieve settling in a very short settling time with BES-TCSC than with the BES alone, and with less device operation.



(a)



(b)



(c)

Fig. 10 Scenario-IV responses, (a) Δf1, (b) ΔPtie12, (c) Δf2.

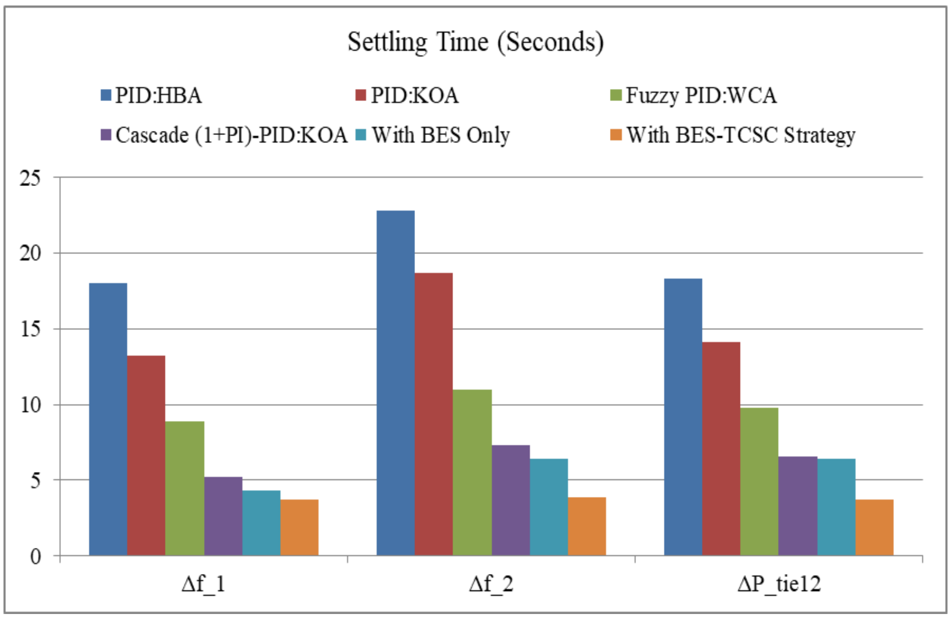


Fig. 11 Performance comparison based on settling time of responses

Table 5. TARPMS system settling time with BES-TCSC integration

Settling time	Without device	With BES only	With BES-TCSC
Δf_1	5.677	5.31	2.63
ΔP_{tie12}	6.495	5.21	2.67
Δf_2	7.32	5.37	2.86

Comparison of settling time of responses with various controllers is given in Figure 11. BES takes care of real power deficit when required, while TCSC is used to damper oscillation in inter area power flow. So, BES-TCSC is the complementary pair to provide the extra control action to IPS for enhanced performance.

6.5. Scenario-V: Sensitivity analysis

The response at the secondary and territory level controls the KOA-tuned (1+PI)-PID cascade controller and BES-TCSC scheme, which is being discussed as a robust performance analysis to verify the validity of the controllers. First, TARPMS responses to the secondary and territory level controls are verified for the ±50% nominal loading, which is given in Figure 12. Finalized from the figure that the response of the system shows a small variation, though the loading varies with 50% range of the nominal loading, and thus it means that the proposed controls can accommodate the change of loading.

Further system is loaded with random changes in loading, and the response is shown in Figure 13. Further, the sensitivity analysis is expanded in the streams of uncertainty in the system, parameters, and the numerical results are presented in Table 6. It can be concluded that the dynamic stability is maintained in the designed system with the case of analyzing with considering the BES-TCSC, compared to the case without. So the designed controllers at secondary and territory levels are found to be robust and able to handle load variations and uncertainties.

Table 6. Settling time of TARPMS with BES-TCSC against parametric uncertainty

Parameter	% deviation	Δf_1	Δf_2	ΔP_{tie12}
Nominal conditions		3.64	3.87	3.68
T_r	+50%	3.95	4.08	3.85
	-50%	3.31	3.69	3.45
T_t	+50%	4.15	4.21	4.11
	-50%	3.28	3.37	3.29
T_w	+50%	4.08	3.96	4.12
	-50%	3.62	3.38	3.52
T_{gh}	+50%	4.22	4.19	4.06
	-50%	3.51	3.29	3.18

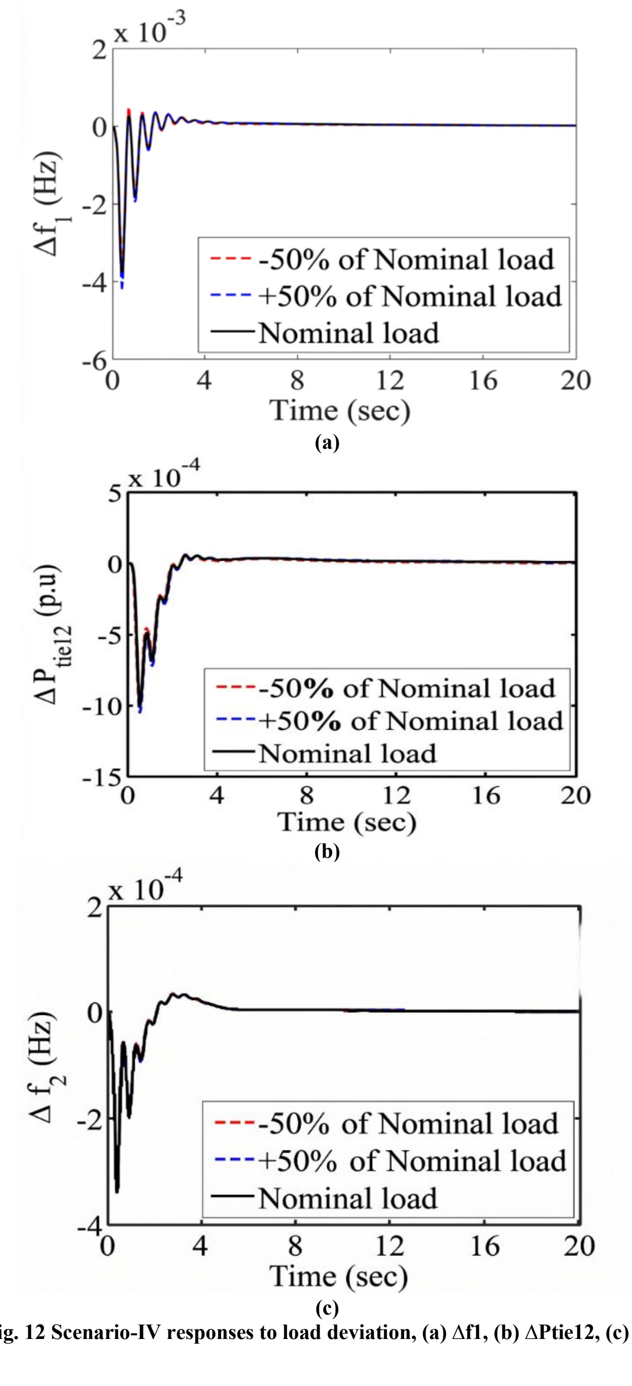


Fig. 12 Scenario-IV responses to load deviation, (a) Δf1, (b) ΔPtie12, (c) Δf2.

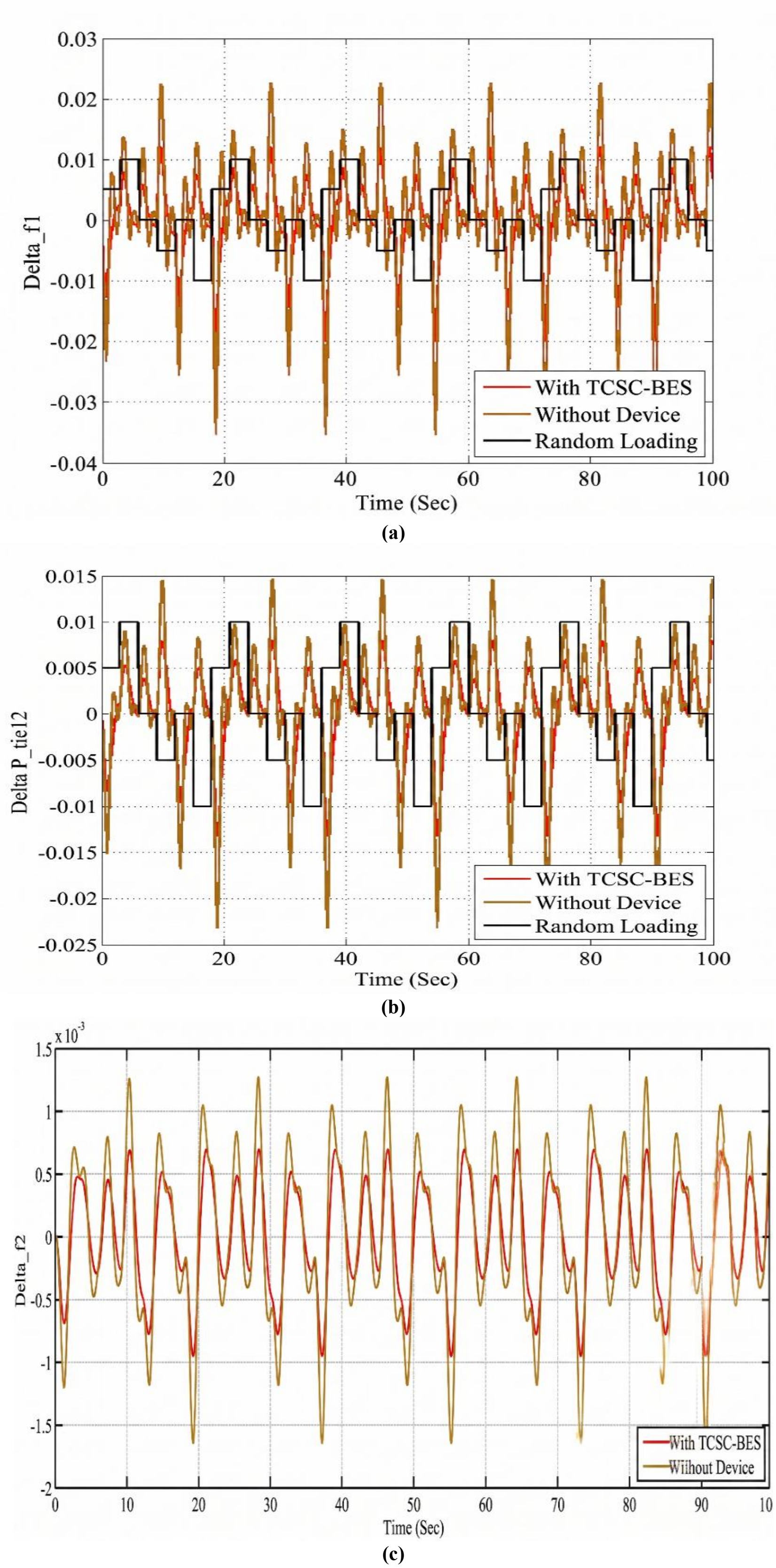


Fig. 13 Scenario-IV responses to random loads, (a) ∆f1, (b) ∆Ptie12, (c) ∆f2.

7. Conclusion

The application of (1+PI)-PID for frequency regulation is emphasized in the proposed work. The KOA method is used for obtaining the optimum controller parameters, and the proposed strategy is verified on the DATH and TARPMS with 10%SLP. The dominance of the proposed control technique is revealed over the methodologies of GWO-based PID, PSO-AHA-based PID, and AO-tuned PID by initially testing it on the DATH model. Moreover, the (1+PI)-PID dominance is visualized across the PID driven by KOA and HBA, and fuzzy PID enforced using WCA by testing it on TARPMS, PID driven with GWO, PSO-AHA, and AO driven FOPID by implementing on the DATH model. For TARPMS, power system generation units are considered with the realistic conditions, i.e., GRC, GDB, and the system with CTDs for the simulation study to make the same nearer to the actual practices. But the system performance due to the effect of these conditions is displayed, and the system is likely to diverge due to the presence of these conditions. The importance of considering these non-linear conditions with IPS in the establishment of a frequency regulator is stated and proved in the study. Additionally, the TARPMS is added by TCSC-BES as an auxiliary controller; In scheme KOA enabled (1+PI)-PID regulator, and the analysis displays the betterment of response in the presence of the auxiliary scheme. At last, the sensitivity analysis confirmed the robustness of auxiliary and (1+PI)-PID driven by KOA mechanisms in attaining the IPS stability even under load uncertainties. In the future, the study can be extended by incorporating the effect of cyber security issues and their subsequent impact on frequency stability.

Conflicts of Interest

The authors stated no conflict of interest.

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