Optimizing Frequency Stability in Interconnected Systems with Renewable Energy and EV Integration

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Optimizing Frequency Stability in Interconnected Systems with Renewable Energy and EV Integration

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Abstract: Maintaining stable frequency in power systems is a persistent challenge, especially in the presence of unpredictable load fluctuations and system nonlinearities. Traditional Load Frequency Control (LFC) methods often struggle to ensure optimal performance particularly when dealing with modeling inaccuracies and external disturbances, i.e. power systems featuring Renewable Energy Sources (RESs) and Electric Vehicles (EVs). To address this limitation, this study proposes and evaluates TID (Tilt Integral Derivative) and FOPID (Fractional Order PID) controllers for a three-area power system comprising Thermal, Hydro, Gas, Geothermal (GTP), and EV based generation. Area-1 encompasses Thermal, EV, and GTP systems with Superconducting Magnetic Energy Storage (SMES); Area-2 combines Thermal and EV units; and Area-3 integrates Hydro, Gas, and EV units. Simulation results in MATLAB SIMULINK under a 0.15 pu (area-1 and area-3), and 0.13 pu (area-2) load disturbance show that the FOPID controller achieves faster settling times and lower oscillations than TID. Specifically, for Area-1, FOPID reduces settling time from 120 seconds (TID) to 110 seconds, with overshoot dropping from 0.0190 to 0.0044 and undershoot from -0.0867 to -0.0465. Similar improvements are observed in Area-2 and Area-3, validating the superior damping and tracking performance of FOPID controllers. Under parameter variation (e.g., KP1 reduced by 10%, TP1 increased by 20% in Area-1), FOPID maintains performance with a maximum settling time of 150 seconds, while TID exceeds 200 seconds. Additionally, incorporating SMES and Thyristor Controlled Phase Shifter (TCPS) further enhances system dynamics. The optimization of controller parameters is performed using the JAYA algorithm. Compared to conventional and recently published methods, the proposed FOPID-JAYA framework offers superior control performance, robustness, and ease of implementation, making it a reliable solution for future smart grids with high RES and EV penetration.

Keywords: area control Error (ACE); electric vehicle (EV); fractional order proportional integral derivative (FOPID); load frequency control (LFC); renewable energy sources (RESs); tilt integral derivative (TID)

1. Introduction

Load variation and disturbances are inherent parts of power system operation. The variations in load occur during the whole day that has to be continuously track for proper and satisfactory working of system. The component that tracks generation and load to keep the system in balance is known as load frequency control (LFC). It balances supply and load demand in a power system by altering the output of generators and helps in a reliable power supply[1-2]. Since load variation change the system's

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frequency, LFC reduces frequency changes at steady state.[3] It also maintains the net power flow between areas at balance. A controller is the main element of LFC which accomplishes this task. A Controller brings back the frequency and power flow back to their normal values. In literature, numerous control schemes starting from conventional to robust, modern, intelligent have been successfully employed to serve the LFC purpose in different power system environment i.e. interconnected and deregulated consisting single area, two area and multiarea structures. Nowadays, the concept of green energy is very popular because of the limited resources of coal and for the protection of environment from harmful effects of coal burning. Therefore, the use and application of renewable energy sources (RESs) in power production is rapidly increasing. It also ensures less polluted and continuous power supply. The integration of RES has increased the responsibility of the LFC because of the intermittent nature of RESs[4]. A controller must be capable of handling abnormalities under all conditions to fulfil his task i.e. settle frequency at its normal value as soon as possible. It is a well-known fact that a controller is as good as its parameters are, which means its parameters must be optimal in the sense that it works efficiently. To get optimal parameters researchers have used various optimization algorithms[5,6]. PID is a well-known controller in LFC; it works effectively however, it gives delayed performance if a system consists any nonlinearity. Therefore, to work effectively in a nonlinear environment, researchers have opted for other control structures. The controller can be used centralized as well as decentralized mode. The efficacy of decentralized PID sliding mode controller with matched /unmatched uncertainties is reported for multiarea power system. PID performance in multiarea power system has been studied. The controller was tested for different load fluctuations cases. A PI-PD droop controller for multisource system is suggested.[10] It shows that the designed controller performs better against parameter variations and disturbances[7-10].

The application of particle swarm based PID (PSO-PID) and Lightning Attachment Procedure based PID (LAPO-PID) controller in hybrid microgrid utilizing Renewable energy resources (RES) has been reported. A novel island consisting of organic Rankine cycle (ORC), wind (WTG), diesel generator (DEG) systems utilizing PI, PID, PID-2DF control approaches has been given. The results showed the superior performance of BESS+SMES system over others. The results also show the superiority of PID-2DF controller over others. An Improved Sunflower Optimization (ISFO) based Type2 Fuzzy PID (T2FPID) controller is designed for hybrid renewable energy system. The results show the supremacy of T2FPID over T1FPID and PID. The performance of the PID controller can be enhanced using the controller based on fractional order techniques. One well known fractional controller which exhibits better flexibility and accuracy over PID is known as fractional order PID (FOPID). A chaos game optimization (CGO) approach utilizing a novel cascade controller is presented. These results showed the dominance of the proposed controller in reducing settling time and deviations. An improved LFC control scheme of hybrid one plus Proportional integral double integral derivative (1+PII2D) and fractional PID (FOPID) for a system having SMES and Flexible AC Transmission Systems (FACTS) has been proposed. The results show the supreme performance of the designed controllers[11-16].

An improved FOPID called MFOPID is presented. The parameters of the designed controller were tuned using Jellyfish search optimizer (JSO). The results evident the better performance of the designed controller for hybrid (gas, reheat thermal, and hydro) and renewable generation sources (solar and wind). A FOPID controller using MOO algorithm for interconnected power system is presented. It is shown that FOPID is better performing than the PID ones. The design/implementation of an improved FOPID scheme is proposed for grid photovoltaic system. The parameters of FOPID are tuned using grey wolf optimization (GWO). The simulation results showed maximum solar power output using proposed controller. The application of FO-AGC for frequency oscillation damping is investigated for hybrid power systems. The results show that controllers can handle higher variations without any decrease in the system performance. A novel concept for frequency and tie-line control for multisource/multiarea deregulated hybrid power systems is presented. Simulations are carried out for different power contracts and load change scenarios. A FOPID controller for distributed energy resources utilizing robust optimization to ensure system frequency for hybrid power system is reported. It is seen that DGs work effectively in LFC and perform well under various operating scenarios. A review study of several LFC structures in various power systems (single area, two area and multi area) with RES is presented[17-23].

The relative analysis of various controllers and approaches were reported. A multiarea power system including thermal, photovoltaic cells, wind turbines, electric vehicle utilizing (1+PI)-PID is reported. The controller is tuned using Bald Eagle Sparrow Search (BESSO) to get optimal gains. It is shown that the proposed controller gives reliable performance. Nowadays, a new control structure, namely TID which is an extension of PID is also being explored by researchers. A multiloop LFC scheme using tilt integral derivative with filter (TIDN) and TDN control schemes has been proposed. A two-area power system with RES and vehicle to grid (V2G) is employed as test system. The results show effective performance. A combined scheme of tilt integral derivative plus filter and hybrid fractional order for robust frequency control is reported. The marine predator algorithm (MPA) is proposed for parameters tuning. The results show the suitability and superiority of the proposed scheme. The performance of TFOID control for frequency regulation has been compared against the performance of PIDF and FOPID control schemes. Five different case have been explored to validate the superiority of the proposed controller. A new controller, namely FOI-PDN, utilizing white shark optimizer (WSO) has been proposed. The designed controller has been checked against FOPID and PID structures. Simulation results show that WSO-FOI-PDN controller successfully reduced peak overshoot, undershoot and settling time. A novel hybrid control architecture 2DOF-PID-TD has been reported. To optimize the proposed controller Artificial Gorilla Troop's Optimizer (AGTO) has been used. The proposed approach has been investigated in multiarea multi source hydro thermal system. A LFC scheme for isolated power systems (thermal, hydro, gas) of multiple sources utilizing PID controller is presented. PSO is utilized for optimal gain of the controller by minimizing IAE, ISE, ITAE, IAE, ISE, ITSE objective functions. The result shows that PSO-PID provides a faster settling time and reduced oscillations than GA-PID, DE-PID[24-30].

A novel fuzzy fractional PI and PIDN controller ($PI^{\lambda}f + PI^{\lambda}DN$), utilizing opposition learning based Volleyball Premier League (OVPL) algorithm has been reported in[31]. This study evident the robustness of the proposed controller against parameter variations while utilizing a modified HVDC tie-line model.

A 2-DOF PID controller with derivative filter in a multi-area system under a deregulated scenario has been presented. Nonlinearities like generation rate constraint (GRC), governor dead band (GDB), and Boiler Dynamics are considered. The system integrates Distributed Energy Systems and Electric Vehicles. Controller gains are optimized using Volleyball Premier League algorithm and tested in MATLAB/Simulink[32].

This paper presents Solid Oxide Fuel Cell (SOFC) power plant integrated into a multimachine system. The model employs a fuzzy logic controller to regulate the current drawn by the power conditioning unit, ensuring it meets the desired output power. The fuel valve is adjusted based on the current. The effectiveness of this scheme has been validated through computer simulations[33].

This paper proposes a demand response strategy to ensure power system reliability amidst increased renewable energy deployment. A modified fuzzy logic control-based 2-DOF fractional PID tilt derivative controller is designed in a hybrid two area restructured system. The controller is optimized using quasi opposition based Harris Hawks Optimization (QOHHO) algorithm. Results show improved system frequency stability compared to existing methods, with experimental validation using OPAL-RT[34].

This paper presents Virtual Inertia Control (VIC) technique applied in a microgrid with intermittent renewable sources. The system includes wind, solar, biogas, and biodiesel plants, with a modified type-II Fuzzy controller optimized using QOHHO algorithm. Results show improved dynamic performance and stability. The proposed VIC strategy outperforms existing methods, demonstrating its effectiveness in maintaining system stability[35].

This article introduces a hierarchical Demand Response (DR) strategy in a multi microgrid system. A Fuzzy PI-PD control scheme is used, with optimal parameters tuned via QOHHO. The study incorporates communication expectancy into the DR loop for improved Frequency Control. Results show that this control scheme outperforms alternative schemes in terms of stability and steady-state error[36]. The impact of various energy storage systems (ESS) on power system stability has been explored utilizing a fuzzy-based controller (PIλDN + FFOPI) controller, optimized using an improved Volleyball Premier League (IVPL). The controller is tested using 2-area and IEEE 39-bus systems under diverse load and parameter conditions. Results confirm the evident performance of the proposed control[37]. This study reported Equilibrium Optimizer (EO) tuned cascaded fractional fuzzy controller (FPIDN-FOPI) for Automatic Generation Control (AGC) in a deregulated power system consisting thermal and gas system with generation rate constraints. The results show the better dynamic performance over conventional methods[38]. This article reported a cascaded Interval Type-2 Fuzzy–FOPIDN controller for AGC in a three area deregulated power system with renewables and distributed generation, utilizing Vehicle to Grid (V2G) support. A modified Quasi-Opposition Arithmetic Optimization Algorithm (QOAOA) is used to tune the designed controller. The result is validated under disturbances via real-time OPAL-RT HIL simulation[39]. This study investigated frequency instability in low inertia microgrids integrating with renewable energy using an adaptive Virtual Synchronous Generator (VSG) for virtual inertia support. A hybrid microgrid with biogas, biodiesel, solar, and wind is controlled via a cascade TI-(1+TD) algorithm, improving system dynamics and compensating the effects of intermittent resources and load deviations[40].

It is a difficult task to choose a right control scheme for LFC, specifically with the integration of RESs and EVs. Although PID is a good controller but with increased system complexity it does not provide satisfactory results. Therefore, other techniques like TID and FOPID and its variation have drawn attention. This paper explores how TID and FOPID control schemes are applied in three power system areas consisting a thermal, geo-thermal (GTP), EV, Hydro, and Gas plants.

The flow chart of the proposed work is given in Figure 1a.

2. Test System

An interconnected hybrid power system is taken as test system in this study. Figure 1b shows three area hybrid power system consisting different generating plants. The complete power system consists of three areas and where each one is connected to others using tie-lines. In between Area-1 and Area-2, a TCPS is also connected for further damping of the oscillations. Various components of the studied power system are as given in next subsections.

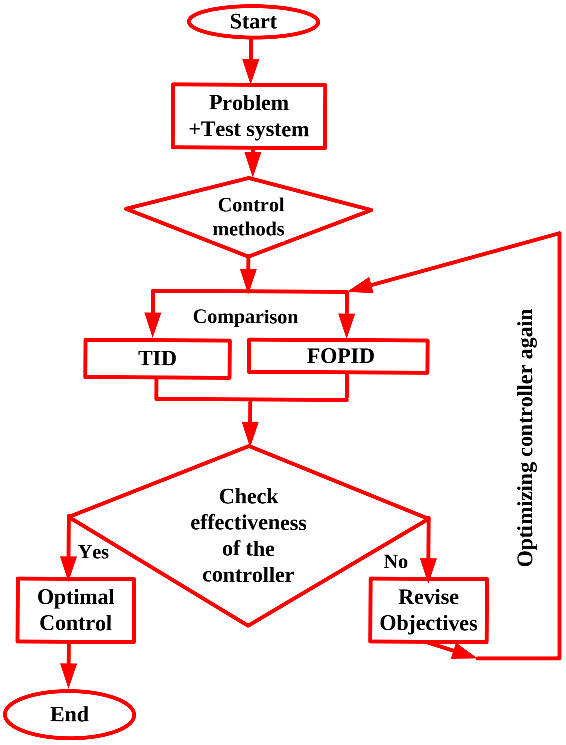

Fig. 1a: The flowchart of the proposed work

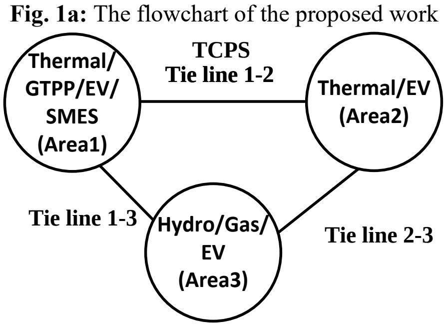

Fig. 1b: Three zone interconnected system

2.1. Electric Vehicle (EVs)

The role of Electric Vehicles (EVs) has been increased in LFC as they can be used in regulation of the system frequency. The charging and discharging of EVs can be modified. Therefore, EVs can help in reducing frequency deviations and provide a balance in supply and demand perturbation. Figure 2 shows EV system and considered parameters are specified in appendix[41)].

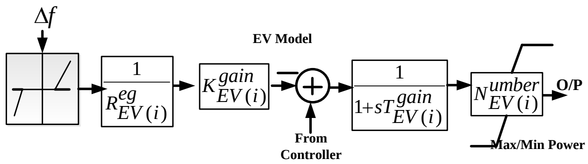

Fig. 2: EV System

2.2. Thermal Power System

The most prominent and main power generating plant is thermal system. Figure 3 depicts the transfer function representation of a reheat thermal system. The load deviation is compensated by using governor-turbine response to balance generation and load demand. The parameters considered are given in appendix[41)].

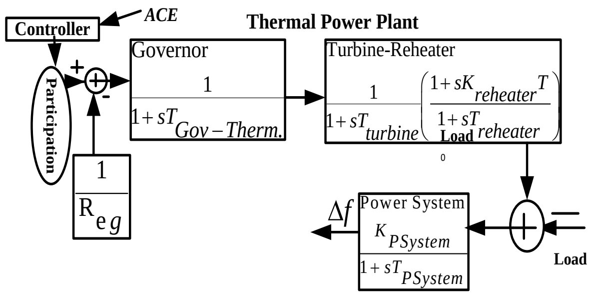

Fig. 3: Thermal System

2.3. Hydro Power System

Hydro power system is used to harvest energy from water. It uses potential energy of water and converts that into electricity. The model of the hydropower system is given in Figure 4. The considered parameters of hydro system are given in appendix[41)].

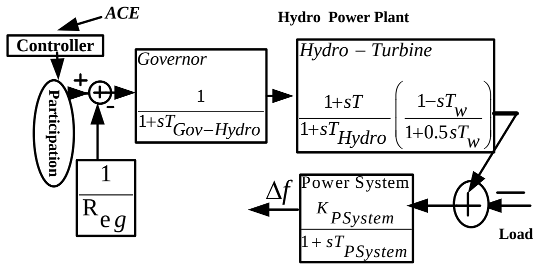

Fig. 4: Hydro System

2.4. Gas Power System

Gas power Plant is used to provide quicker response for any load change. Figure 5 represents the Gas power system. The considered parameters of gas power Plant are given in appendix[41)].

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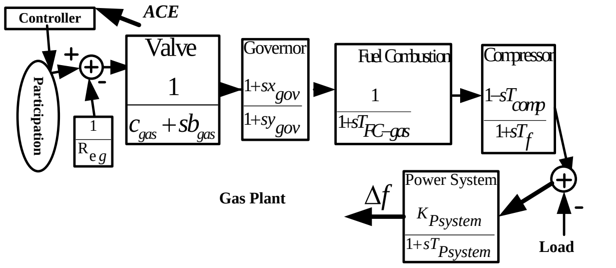

Fig. 5: Gas Power Plant

2.5. Geo-Thermal Power System

The transfer function representation of a Geo-thermal plant (GTP) is represented in Figure 6. GTPs are popular as they can use heat energy and converted into electricity like the power production of thermal plants. The parameters are given in appendix[41)].

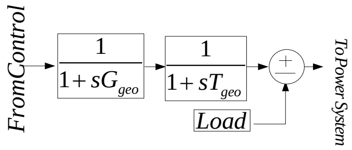

Fig. 6: GTP Model

2.6. Super Magnetic Energy Storage Device (SMES)

SMES is used to provide fast response. It works as the first protection against any load deviation by injecting real power to the power system. Figure 7 shows SMES model and parameters are given in appendix[41)].

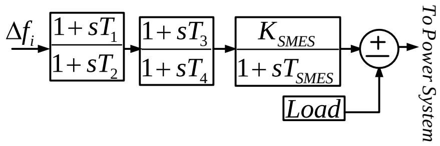

Fig. 7: SMES Model

2.7. Thyristor Controlled Phase Shifter (TCPS)

TCPS is used to control or limit oscillations/time of the deviations. Figure 8 represents a model of TCPS. In this study, TCPS is in Area-1 and connected to tie-line. The parameters are given in appendix[41)].

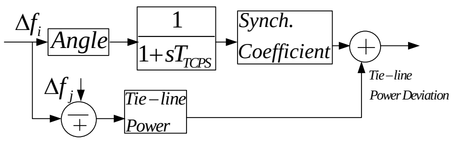

Fig. 8: TCPS Model

The complete model of three area hybrid power system including all generating plants and load is given in Figure 9.

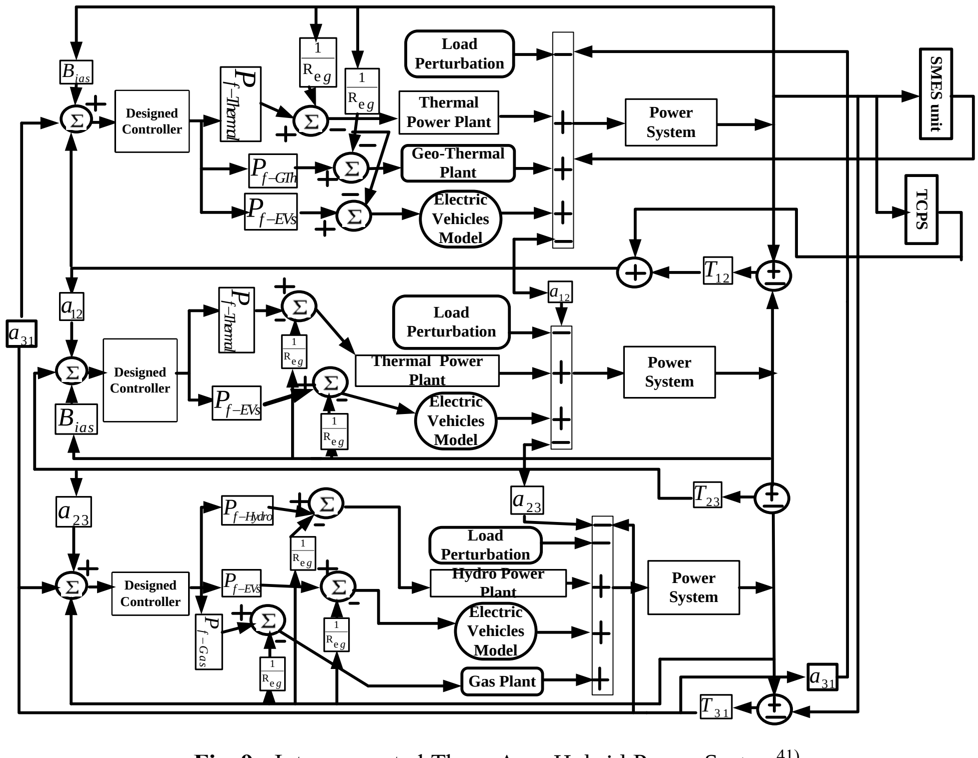

Fig. 9: Interconnected Three-Area Hybrid Power System[41)]

3. The Designed Control Schemes

For any LFC scheme, a controller is used to keep the system's frequency and tie-line power in definite limits and keep system in balance. In this paper, TID and FOPID controllers have been tested for the system shown in Figure 9.

3.1. TID Control Scheme

The Tilted Integral Derivative (TID) focuses on improving PID performance by altering the PID design. TID controller modifies PID controller by replacing Proportional term with tilted component. TID combines the effects of integral and derivative more effectively and gives robust performance to improve system stability[25]. TID controller overcomes disturbance rejection and reduces overshoot more effectively than PID. The structure of TID control scheme is represented in Figure 10[26]. The mathematical model of TID controller is given in Eq. 1[27].

$$G_{TID}(s) = K_T s^{\left(-\frac{1}{n}\right)} + \frac{K_I}{s} + K_D s \quad (1)$$

Where, K_T, K_I, and K_D = TID parameters.

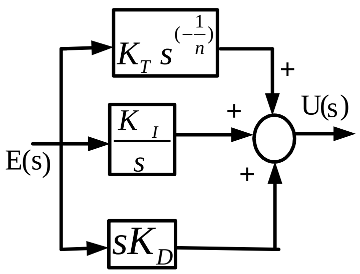

Fig. 10: TID Control Scheme

3.2. FOPID control Scheme

FO based controllers are increasingly favored for their flexibility and expended degree of freedom. It offers more precise control. It also offers more stability in the region, and greater design of controllers. FOPID is a well-known control scheme among FO controllers shown in Figure 11. It is based on fractional calculus and was proposed by Oustaloup[11-15]. It has two extra parameters than PID to tune the system more effectively. FOPID controller can be characterized mathematically as given in Eq. 2.

$$U(t)=K_{Pf}.E(t) + \frac{K_{If}}{s^{foI}}.E(t)+K_{Df}s^{foD}.E(t) \quad (2)$$

where, D = $\frac{d}{dt}$. The Laplace form of eq (2) is given in Eq (3).

$$U(s) = \left[K_{Pf} + \frac{K_{If}}{s^{foI}} + K_{Df}s^{foD}\right] \quad (3)$$

where K_{Pf}, K_{If}, K_{Df} = FOPID gains, foI and foD = fractional integrator and differentiator.

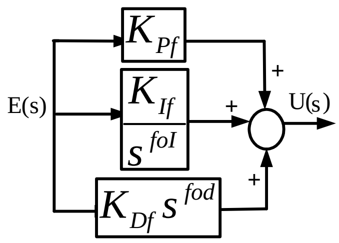

Fig. 11: FOPID Control Scheme[31]

4. The Optimization Approach

An effective controller is characterized by its optimal parameters. Various optimization algorithms have been employed in history to design controller parameters. In this paper, the authors achieved optimal parameters using a recently developed algorithm.

4.1. JAYA Algorithm

JAYA algorithm uses Exploration- Exploitation to modify the current solution and gives quick convergence to perform optimally[32-35]. The procedure for designing a controller using Jaya algorithm is outlined below:

Step1: Optimize the objective function shown in Eq. 4, where, N= number of areas.

$J = \frac{1}{N}\sum_{i=1}^{N}[(ACE_i)^2]$ (4)

Step2: Initialize the population for each control scheme.

Step3: Calculate objective function (step1) to get fitness function.

Step4: Based on the worst and best fitness, parameters are updated.

$P_{i,j}^{new} = P_{i,j}^{Cr} + rand_1(P_{i,j}^{Bs} - \left|P_{i,j}^{Cr}\right| - rand_2(P_{i,j}^{Wr} - \left|P_{i,j}^{Cr}\right|$Where,

$P_{i,j}^{Cr}$ = currentvalueof$P_{i,j}^{Wr}$ j^{th}parameter, i^{th}solution

$P_{i,j}^{Bs}$ = j^{th}parameterofbestsolution

$P_{i,j}^{Wr}$ = j^{th}parameterofworstsolution

$rand_1$,$rand_2$=random_number

Step4: Comparison between new and old solutions are carried out and old is replaced with new ones, if it is better.

Step5: It identifies the optimal parameters of halts if the threshold criteria are met.

5. Results and discussions

The whole system is simulated in SIMULINK/MATLAB environment to examine how well the performance of the designed control schemes is. The following scenarios have been considered to check the controller's effective performance.

5.1. Case 1

This case considers the following load perturbations: step load =0.15 pu (Area-1), step load= 0.13 pu (Area-2) and step load=0.15 pu (Area-3). The simulation is run for normal parameters of each control area. The considered load deviation is shown in Figure 12.

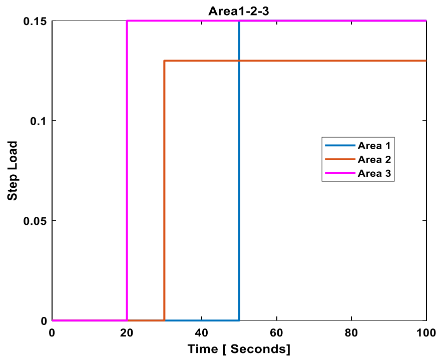

Fig. 12: Step Load in All Areas

5.1.1. *Frequency Deviations Result Analysis*

The deviations in frequency of each area are given in Figure 13a, Figure 13b and Figure 13c. Fig 13a shows frequency deviation for Area-1. Similarly, Figure 13b and Figure 13c shows frequency deviations in Area-2 and Area-3, respectively. It is evident from the results that in each area the frequency is settling down to its nominal value. Both controllers are performing their task well, however, FOPID controller is an outsmart TID controller as it settled down the deviations in a smaller time with smaller oscillations than TID controller. Frequency deviations with TID controller are of large magnitude and have larger settling time than the FOPID controller. FOPID's ability to handle complexity and providing more flexibility results in lower frequency deviations and quicker stabilization in all areas.

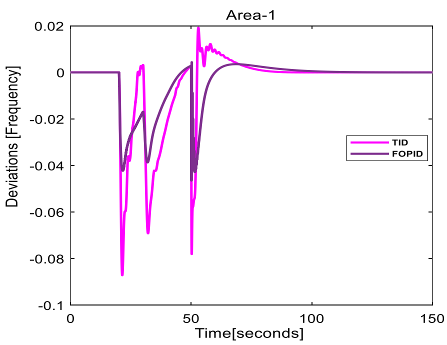

Fig. 13a: Frequency (Area-1) Deviations

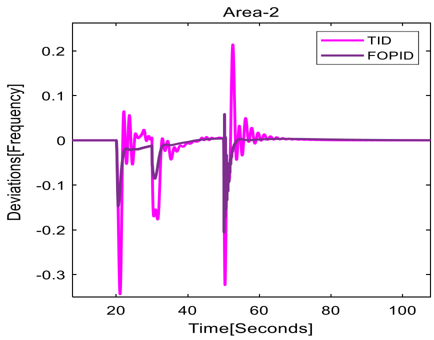

Fig. 13b: Frequency (Area-2) Deviations

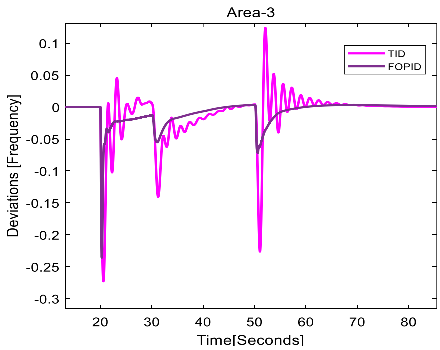

Fig. 13c: Frequency (Area-3) Deviations

5.1.2. *Change in Generation* Result Analysis (Area-1)

The overall change in generation in Area-1 is given in Fig 14. Since a total load of 0.15 pu occurs at Area-1, it has to be carried by the generating plants of Area-1 only. So, to fulfill this demand all three power sources of Area-1 alter their power generations. Figure 14a shows the net change using GTP. Similarly, Figure 14b and Figure 14c shows the net change in Thermal and EV power system. All the given Figures show effective results of FOPID scheme over TID scheme. Although TID control approach is good and settled the generations at their specified values, they have the problems of overshoot and prolonged settling time. The FOPID controller improves control accuracy and response times leading to a more specific and gives quicker changes in generation, reducing overshoot, achieves desired power changes while TID shows the effective but longer response time performance.

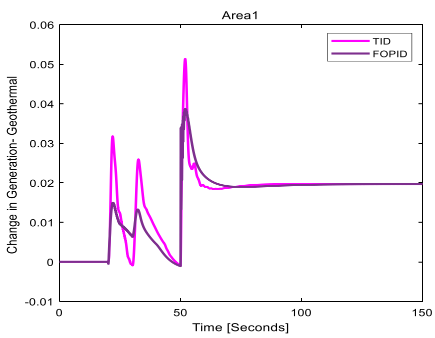

Fig. 14a: Generation Change in Area-1 (GTP)

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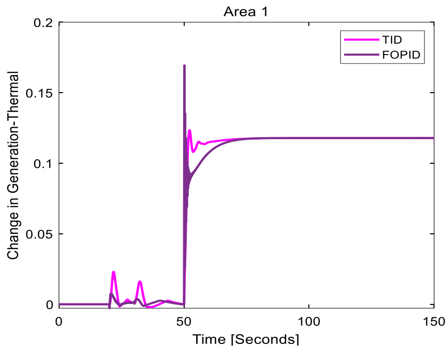

Fig. 14b: Generation Change in Area-1 (Thermal)

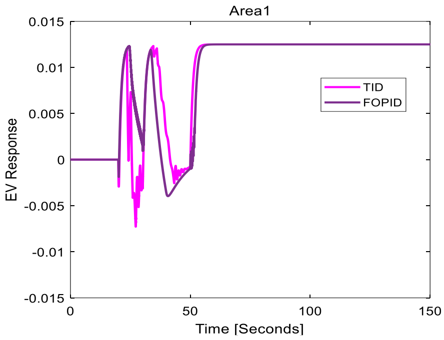

Fig. 14c: Generation Change in Area-1 (EVs)

5.1.3. *Change in Generation* Result Analysis (Area-2)

To respond against a load demand of 0.13 pu in Area-2, generating stations of Area-2 acted accordingly. Figure 15a shows the change in thermal and Figure 15b shows the response of electric vehicle (EV) in Area-2. It is apparent that FOPID ensures quick and reliable generation and provides more precise and quicker control.

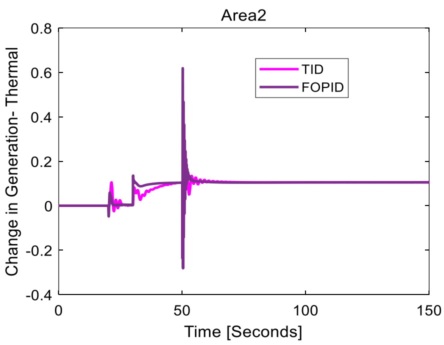

Fig. 15a: Generation Change (Thermal) Area-2

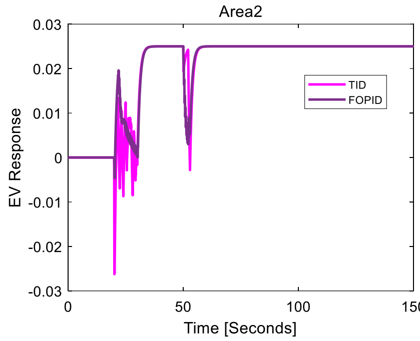

Fig. 15b: EV Response in Area-2

5.1.4. *Change in Generation* Result Analysis (Area-3)

Hydro, EV, and Gas generating plants in Area-3 responded well against a perturbation of step load of 0.15 pu. The change in generation of each is shown in Figure 16a, Figure 16b and Figure 16c. It is clearly indicated from the results that the FOPID gives effective working and settles each generating plants at their desired value in quick and precise control. TID controllers, though accomplished, face complications of overshoot and large settling time.

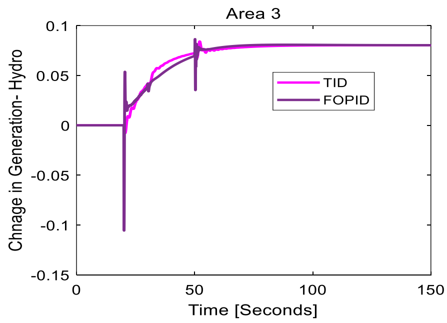

Fig. 16a: Generation Change (Hydro) Area-3

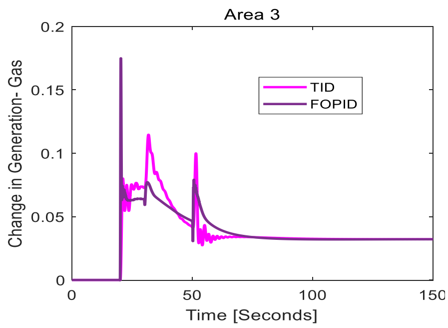

Fig. 16b: Generation Change (Gas) Area-3

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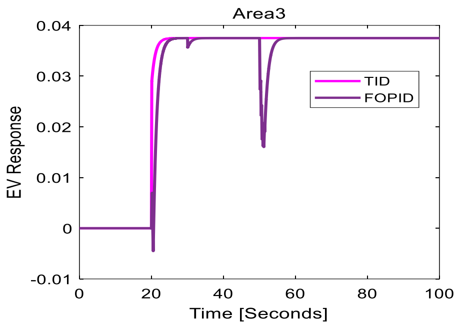

Fig. 16c: EV Response in Area-3

5.1.5. *Tie -Line Power Result Analysis*

The tie line flows the power to and from a control area. It is an important factor that is necessary for power exchange in between areas. Tie-line power flow results are shown in Figure 17a, Figure 17b, and Figure 17c for different areas. It is seen that FOPID scheme works better and reduces tie-line oscillations with smaller oscillations than TID scheme.

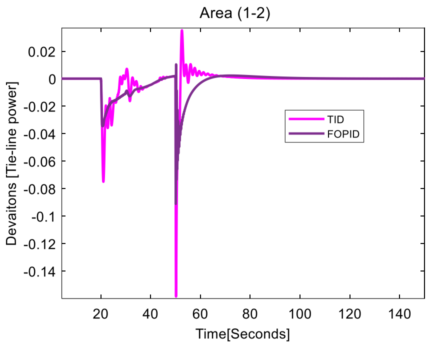

Fig. 17a: Tie-Line Power Deviations (Area 1-2)

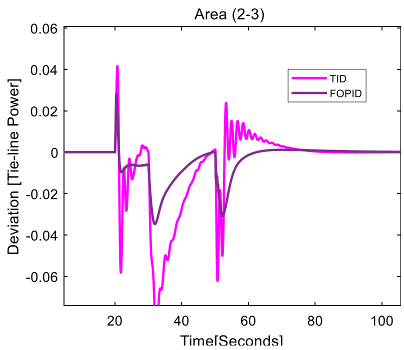

Fig. 17b: Tie-Line Power Deviations (Areas2-3)

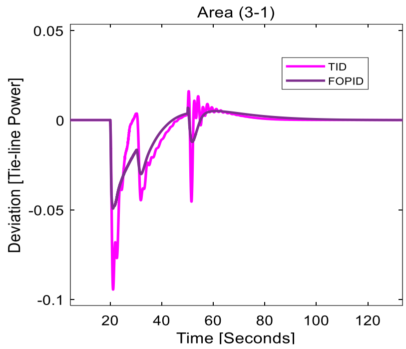

Fig. 17c: Tie-line Power Deviations (area 3-1)

5.1.6. *Area Control Error (ACE) Result Analysis*

ACE is a measure of net distribution of the generation. ACE large value means the area is oversupply and a lower value of ACE means the area is not able to supply the demand. Figure 18a shows the ACE graph for Areas 1-2, similarly, Figure 18b and Figure 18c shows ACE among other areas. It is seen from the results that at a steady state ACE is settling to the desired value, however, FOPID performs best than TID in all areas. FOPID provides more accurate and better steady state performance.

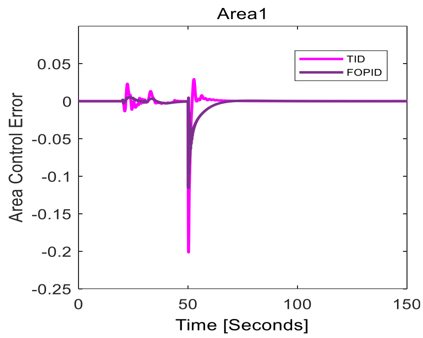

Fig. 18a: Area-1 control Error

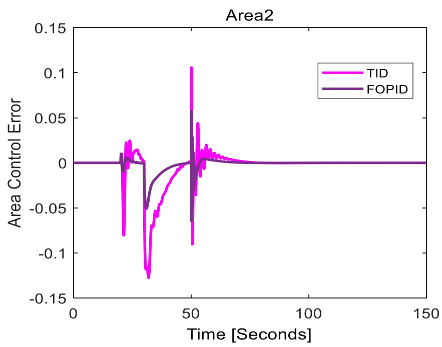

Fig. 18b: Area-2 Control Error

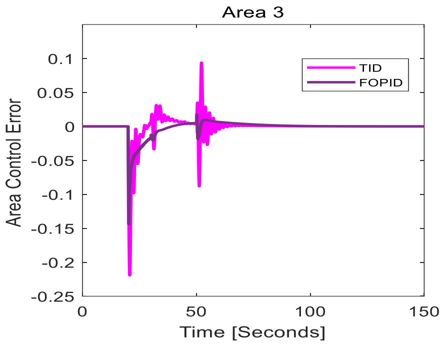

Fig. 18c: Area-3 Control Error

5.2. Case 2

This case considers the following load perturbations: step load =0.2 pu (Area-1), step load= 0.15 pu (Area-2) and step load=0.15 pu (Area-3). The simulation is run for changed parameters of each control areas to see that the designed controller is capable to handle parameter variations or not. Table 1 shows the parameters for which this case has been simulated.

Table 1: Change in Parameters

Area	Parameter	Percentage Change
Area-1	KP_1	10% Drop
	TP_1	20% Rise
Area-2	KP_2	20% Rise
	TP_2	50% Rise
Area-3	KP_3	25% Drop
	TP_3	15% Drop

5.2.1. *Frequency Deviations Result Analysis*

Figure 19a, Figure 19b and Figure 19c shows the frequency deviation for this case in Area-1, Area-2 and Area-3 respectively. The analysis reveals that both contorl schemes manage the parameter variations but the TID control scheme has larger oscillations. The main finding is that TID has increased settling time than the normal parameters case. However, FOPID controller performance remains the same as earlier. So it can be concluded that FOPID manages parameter variations more effectively than TID.

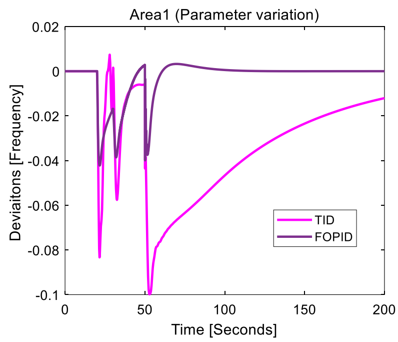

Fig. 19a: Frequency (Area-1) Deviations (parameter variation)

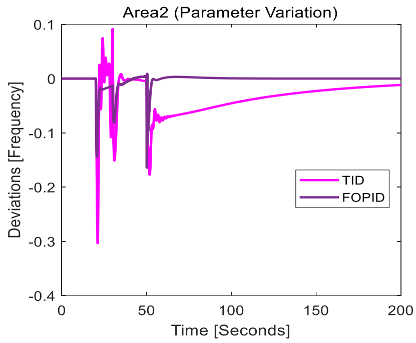

Fig. 19b: Frequency (Area-2) Deviations (parameter variation)

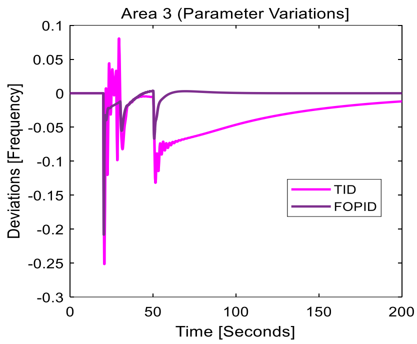

Fig. 19c: Frequency (Area-3) deviations (parameter variation)

5.3. Case 3

This case is like Case 1, however it includes the effects of SMES and TCPS.

5.3.1. Frequency Deviation (with SMES)

SMES is used to release energy as and when use. It also helps to reduce the oscillations in response. It can be seen from the result obtained for frequency deviations (Fig 13). It typically exhibits larger and more prolonged oscillations. However, with SMES, the frequency deviation is reduced in both settling time and oscillations. The rapid response of SMES enables it to counteract deviations almost instantly, allowing the system to return to its nominal frequency much faster, as shown in Figure 20.

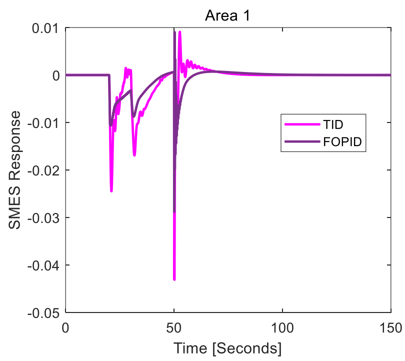

Fig. 20: Frequency (Area-1) Deviation (SMES)

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5.3.2. Tie-line Power Deviations (TCPS is included)

The Enhancements in tie-line power depend on the adjustment and accurate controlling of the phase angle, which is necessary for the flow of power of the power. This power is exchanged between areas. TCPS is used to control this phase angle for accurate power flow. Figure 21 shows that tie-line power deviation has larger magnitude and oscillation without TCPS while in presence of TCPS, it shows reduced oscillations and settling time.

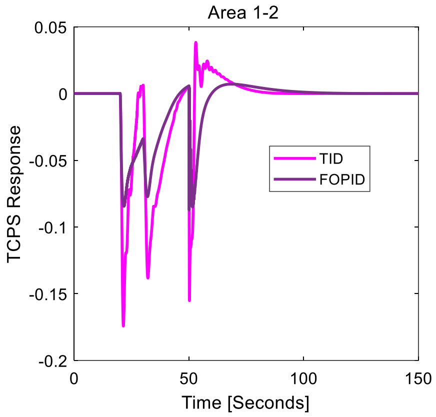

Fig. 21: Tie-line (area1-2) Power Deviations (TCPS)

The optimized parameters of the controller have been given in Table 2. Table 3 demonstrates the comparative performance of both the controllers for normal parameters. Table 4 compare the performance of the control schemes for parameter variation case.

Table 2: Optimal parameters for designed controllers

Controller	Area	Coefficients	
TID	Area-1	-0.07/-0.023/-2.36/5.32	$K_T/K_I/K_D/n$
	Area-2	-0.1/-0.23/-1.01/5.26	
	Area-3	-0.15/-0.856/-0.1/1.1	
FOPID	Area-1	-1.5/-1.53/-1.9/1.2/1.1	$K_P/K_I/K_D$ /L/M
	Area-2	-1.8/-1.86/-1.7/1.6/1.7	
	Area-3	-1.2/-1.86/-1.15/1.8/1.9	

Table 3: Performance of controllers for normal parameters

Parameter	Controller	Overshoot	Undershoot	Settling Time (seconds)	Parameter	Controller	Overshoot	Undershoot	Settling Time (seconds)
Frequency (Area-1)	TID	0.0190	-0.0867	120	Tie-line (1-2)	TID	0.0348	-0.1579	130
	FOPID	0.0044	-0.0465	110		FOPID	0.0102	-0.9107	120
Frequency (Area-2)	TID	0.02134	-0.3439	130	Tie-line (2-3)	TID	0.04115	-0.09071	135
	FOPID	0.05814	-0.2057	120		FOPID	.00123	-.03073	120
Frequency (Area-3)	TID	0.1235	-0.2728	145	Tie-line (1-3)	TID	.01546	-0.0944	130
	FOPID	0.0035	-0.2358	140		FOPID	.00521	-.04931	120

Table 4: Performance of controllers for parameters variation (Robustness/stability)

Parameter	Controller	Settling Time (seconds)
Frequency (Area-1) Deviations	TID	>200
	FOPID	150
Frequency (Area-2) Deviations	TID	>200
	FOPID	140
Frequency (Area-3) Deviations	TID	>200
	FOPID	145

5.4. Stability analysis

Stability of the system is validated using both time-domain simulations and performance indices including settling time, overshoot, and Area Control Error (ACE). Time-domain responses under a 0.15 pu step load disturbance show that in Area-1, the FOPID reduces the frequency deviation settling time from 120 s (TID) to 110 s, while also minimizing overshoot from 0.0190 to 0.0044 and undershoot from -0.0867 to -0.0465. Similar improvements are noted in Area-2 and Area-3. Under parameter variation (e.g., 10% reduction in KP1, 20% rise in TP1), FOPID maintains performance with a maximum settling time of 150 s, while TID exceeds 200 s, indicating diminished robustness. Furthermore, the inclusion of SMES and a Thyristor Controlled Phase Shifter (TCPS) reduces oscillations in both frequency and tie-line power, reinforcing system damping (Figs 20-21). The overall analysis confirms that FOPID not only improves dynamic response but also enhances the stability margins of the multi-area power system under high RES and EV penetration, making it a superior choice for modern power system LFC applications.

5.5. Main Contributions

The paper presents a Load Frequency Control (LFC) for a multi area hybrid power system with integration of Renewable Energy Sources (RESs) and Electric Vehicles (EVs). The main contributions of this works are:

Novel Comparative Analysis: A comparative study of two control approaches namely Tilt Integral Derivative (TID) and Fractional Order PID (FOPID) in a complex three-area power system integrating thermal, hydro, gas, geothermal, and EV-based generation.

Integration of Advanced Components: This study also incorporates Superconducting Magnetic Energy Storage (SMES) and Thyristor controlled phase shifter (TCPS) into the system model to further enhance frequency regulation and reduce oscillations in the tie line power flow.

Robust Optimization using JAYA Algorithm: The paper utilizes the JAYA algorithm to obtain controller parameters, which eliminates the need of algorithm-specific parameters making the approach simpler and more adaptable.

Performance under Parameter Variations: This study also evaluates controller robustness by simulating performance under parameter variations.

Demonstrated Superiority of FOPID: The results decisively show that the FOPID controller outperforms the TID controller in terms of settling time, overshoot, undershoot, ACE minimization, and tie-line deviations.

5.6. Comparative Validation with Recent Works:

To establish the efficacy of the proposed FOPID JAYA control framework, its performance was compared with the techniques reported in recent literature. The proposed method achieved a settling time of 110 s in Area-1 under a 0.15 pu load step, which is faster than the MPA-tuned TFOID controller (Case 3: settling time ~130–140 s) reported in Ahmed et al. [IEEE Access, 2021]. Additionally, the proposed scheme achieved an overshoot reduction of more than 50% and enhanced robustness against parameter variations, maintaining stability with less than 150 s settling time compared to >200 s for TID. Unlike the GWO- and PSO-based FOPID controllers which require careful algorithm-specific parameter tuning, the JAYA algorithm offers parameter-less operation with comparable or better convergence and accuracy [Xu et al., Mathematics, 2023]. Furthermore, inclusion of SMES and TCPS in the proposed system reduced tie-line oscillations and improved frequency regulation, which has not been concurrently addressed in most recent studies. These comparative results affirm the superiority of the proposed FOPID JAYA controller in terms of response, robustness, and applicability to modern grid environments.

Summarise view: The proposed FOPID-JAYA controller achieves:

Lowest settling time (110 s for Area-1) among recent methods.

Significant overshoot reduction (e.g., 0.0044 vs. 0.0190 for TID).

Better robustness to parameter variations, maintaining performance under ±25% gain/time constant changes.

Simplified optimization using the JAYA algorithm, which requires no control parameters, unlike GWO, PSO, or MPA.

This comprehensive performance superiority demonstrates that the proposed method is effective, efficient and practical for smart grid environments.

6. Conclusion

The study proposed a robust and adaptable Load Frequency Control (LFC) strategy for a complex multi-area hybrid power system that integrates Renewable Energy Sources (RESs) and Electric Vehicles (EVs) alongside conventional sources such as Thermal, Hydro, Gas, and Geothermal power plants. To enhance stability the system model also incorporates Superconducting Magnetic Energy Storage (SMES) and Thyristor Controlled Phase Shifter (TCPS). The control involved a comparative analysis of two advanced schemes namely, Tile Integral Derivative (TID) and fractional order PID (FOPID). A key novelty of this work lies in the use of the JAYA optimization algorithm for tuning both TID and FOPID controller parameters, ensuring robustness and adaptability by simplifying the optimization process.

Extensive time-domain simulations under both normal and parameter variation scenarios demonstrated that the FOPID-JAYA control strategy consistently outperforms TID in terms of frequency stabilization, tie-line power control, and Area Control Error (ACE). Notably, the FOPID controller reduced frequency settling time by 8–15% and overshoot by more than 50% compared to TID, validating its effectiveness in handling the dynamic uncertainties of modern power systems. The inclusion of SMES and TCPS (Fig 20 and Fig 21) further enhanced frequency response and reduced oscillations, adding another layer of practical innovation to the system architecture. The proposed framework achieves superior results in both control performance and system stability. The overall analysis shows that FOPID is better and reliable solution for LFC in future smart grids.

Future Applicability and benefits

The proposed FOPID-JAYA framework has proven effective for frequency regulation in a multi-area hybrid power system; however, several research directions remain open due to its robustness, scalability, feasibility in real time and readiness.

Future work will focus on real-time implementation in Hardware in the loop (HIL) or OPAL-RT environments, to validate its practical feasibility.

Additionally, integrating adaptive or machine learning-based tuning techniques could further improve controller performance under highly uncertain and stochastic scenarios, such as high RES variability or cyber-physical threats.

Exploring other fractional order and robust control strategies in combination with coordinated voltage control could also be beneficial in enhancing system-wide resilience.

Overall, this work establishes FOPID-JAYA as a high performance, future ready control strategy in order to achieve stable and reliable frequency regulation in modern, intelligent systems.

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Apendix (Ref 41)

Thermal Power System

$Time\ constants\ of\ the\ governor = T_{Gov-Therm.} = 0.08s$

$Time\, cons\tan t\ of\ Turbine = T_{turbine} = 0.3s$

$Time\ constants\ of\ the\ \mathrm{Re}\, heater = T_{reheater} = 10s$

$K_{reheater} T = 120$

$Time\ constants\ of\ the\ System = T_{PSystem} = 20s$

$\mathrm{Regulation}(\mathrm{R}_{eg}) = 2.4$

Hydro Power System

$Governor\ Time\ Constant = T_{Gov-Hydro} = 0.513s$

$Water\ starting\ time = T_w = -1s$

$Transient\ droop\ time\ constant = T_{Hydro} = 48.7s$

$Reset\ time\ constant = T = 5s$

Gas Power System

$Valve\ position = c_{gas} = 0.2s$

$valve\ positioner\ constant = b_{gas} = 1s$

$Lead - Lag\, Time\, constt = x_{gov} / y_{gov} = 0.6s / 1s$

$compressor\ discharge\ volume = T_{FC-gas} = 0.049s$
$Combustion\ reaction\ time\ delay = T_{comp} = -0.01s$
$Fuel\ time\ Constt = T_f = 0.239$
Electric Vehicle
Charging and discharging capacity = ±5 kW.
$EV\ gain = K_{EV(i)}^{gain} = 1$, $T_{EV(i)}^{gain}$=1, $N_{EV(i)}^{umber}$=500, 1000, 1500.
A dead band (+/-10Mhz), Droop coefficient= 2.4 Hz/pu.
Geo Thermal Power Plant
$Time\,constt\,Governor = T_{geo-t} = 0.1s$
$Time\,constt\,Turbine = T_{s-geo} = 0.5s$
SMES
T_1 =0.2333s, T_2= 0.16s, T_3=0.7087s, T_4=0.2481s, K_{SMES}=0.205, T_{SMES}=0.03s
TCPS
K_{TCPS}=2, T_{TCPS}=0.02s