Coordinated IPFC and SMES Strategy for Stability Analysis of Renewable Energy Based Contemporary Interconnected Power System with FOPID Controller

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Abstract- In this paper, an amalgamation of fractional calculus theory with integral order (IO) controller that is fractional order PID (FOPID) fine-tuned with water cycle algorithm (WCA) a natured inspired optimization technique is proposed as a secondary regulator for renewable-based contemporary interconnected power system (IPS). Investigation performed on IPS subjected to the perturbations of 10% step load on area-1 (10%SLP). System nonlinearity features of communication time delays (CTDs) are considered to conduct a more realistic analysis. Simulation results reveal the predominance of CTDs on IPS performance. The sovereignty of presented FOPID has been demonstrated with traditional IO type regulators like PI, and PID under unique perturbed conditions. Further, the device superconducting magnetic energy storage (SMES) is incorporated in each area and the interline power flow controller (IPFC) is operated in conjunction with the tie-line is operated. Responses of IPS reveal the enhancement in the dynamic performance of the system under the coordination of IPFC-SMES with the WCA tuned FOPID regulator.

Keywords FOPID regulator, Water cycle algorithm, SMES-IPFC strategy, CTDs, 10%SLP.

1. Introduction

Today's world is more focusing on reducing carbon emissions to control global warming. Moreover, the fossil fuels which constitute the carbon emissions in the environment are rapidly depleting. With the motto of handover of fossil fuels to future generations and minimizing their effect of emissions on the modern-day environment, renewable power generation units are gaining momentum in the electrical sector. With the rapid growth of industrialization, the electricity demand is continuously increasing. To meet the load demands, renewable power-generating sources (RPGS) are extensively integrated with the existing grid. The IPS network is becoming complex with RPGS integration and requires more sophisticated control techniques to ensure IPS stability and reliability.

The entire IPS is segregated into various control areas and each area is integrated with different power generation sources. The control areas are together interlinked with a transmission line called a tie-line to facilitate power exchange. Tie-line power and control area frequency deviations are power full indicators in assessing the stability, reliability and security of large scale IPS networks. The deviation in control area frequency arises with the lapse between the generation of real power and existing load demand. Thus the lapse between power generation and demand must be monitored and regulated continuously and automatically. The automatic action is filled by employing the load frequency controller (LFC) in each control area. A bulk quantity of literature is reported on LFC study and researchers are proposed numerous control technics and their efficacy is tested by considering various power system models as test systems [1].

Owing to the advantage of conventional controllers like PI and PID [2] in design simplicity, researchers are widely implemented as secondary regulators to LFC study. Moreover to make the controller performance more effective, researchers are adopted various meta-heuristic optimizations like Salp swarm technique (SST), fruit fly algorithm (FFA) [3], imperialist competitive approach (ICA), dragon search optimizer (DSO), flower pollination (FPA) algorithm [4], modified bat algorithm (MBA), multi verse optimizer (MVO), whale optimization technique (WOT), ant lion optimizer (ALO) [5], chemical reaction optimizer (CRO), genetic algorithm (GA) [6], seagull optimization algorithm (SOA) [7], simulated annealing (SA), firefly algorithm (FA) [8], marine predictive approach (MPA) [9], teaching learning based (TLBO) [10], optimizer, water cycle algorithm (WCA) [11-12], elephant heard technique (EHT) [13], artificial field algorithm (AEFA) [14], fractal search-pattern search (FSPS) [15], gravitation search technique (GST), backtracking search algorithm (BSA) [16], particle swarm optimizer (PSO) [17], squirrel search algorithm (SSA), cuckoo search technique (CST) [18], grey wolf optimizer (GWO) [19], biogeography optimizer (BGO), moth flame optimizer (MFO) [20], mine blast technique (MBT), bacterial foraging algorithm (BFA) [21], differential evolution (DE) [22], quasi-oppositional GWO, etc. are reported. But the PI and PID regulators are best suitable for only models of linearized characteristics.

In realistic practice, no power system network is linear and has deliberated with generation rate constraints (GRC), a practical non-linearity feature to regulate the generation lowering and rising. Thus, researchers are focused on implementing fuzzy logic control (FLC) techniques for LFC in association with PI and PID. Different FLC controllers such as WCA based fuzzy (F) PID [23], big bang-big crunch (BBBC) [24] tuned FPID, and SA based FPI [25], ICA [26] tuned FOFPI-FOPD is available in past studies. The design of FLC is more complex and requires skilled technicians. Moreover, the framing of fuzzy rules and selection of membership functions greatly influences FLC performance.

Further, researchers are focused on the design of sliding mode controllers (SMC) and robust control techniques. However, the robust control technique involves more mathematical modelling and its application to complex IPS are time taking. Thus, FO controllers are gaining momentum and are more efficacious compared to traditional regulators. FOPI, FOPI-FOPD and FOPID are based on optimization algorithms like the sine cosine approach (SCA) [27], CRO, Falcon optimizer (FO) [28], Volleyball algorithm (VBA) [29], lion algorithmic approach (LAA) [30], lightning search algorithm (LSA), crow search technique (CST) etc. are reported.

A literature survey discloses that FOPID based on SOA is not available in the literature. SOA is the latest technique and is widely grabbing the attention of researchers as a solution to engineering problems. Apart from the secondary control techniques, territorial strategy is necessitated for the contemporary IPS with RPGS as the power generation from renewable units is very intermittent. Implementation of high voltage DC transmission line with AC tie-line is rigorously implemented by the researchers [31]. Contrary to AC-DC lines, coordinated flexible AC transmission system devices and energy storage devices (ESDs) are newly implemented by researchers [32].

Considering the above literature this paper contributes the following.

a) Contemporary renewable-based IPS is designed in MATLAB/SIMULINK.

b) WCA based FOPID is implemented as a secondary regulator in each control area.

c) Efficacy of FOPID is deliberated with PI, and PID performances.

d) Contemporary IPS are investigated with and without CTDs considerations.

e) The impact of CTDs on contemporary IPS performance is visualized and justified.

f) SMES-IPFC coordinated control is implemented for performance enhancement.

g) The sensitivity test is conducted to demonstrate secondary and territorial strategy robustness.

2. Introduction

Contemporary IPS considered for investigation in this paper comprises two areas having a 5:3 generation ratio. Area-1 consists of traditional power generations of thermal, hydro and gas with a total capacity of 1250MW.

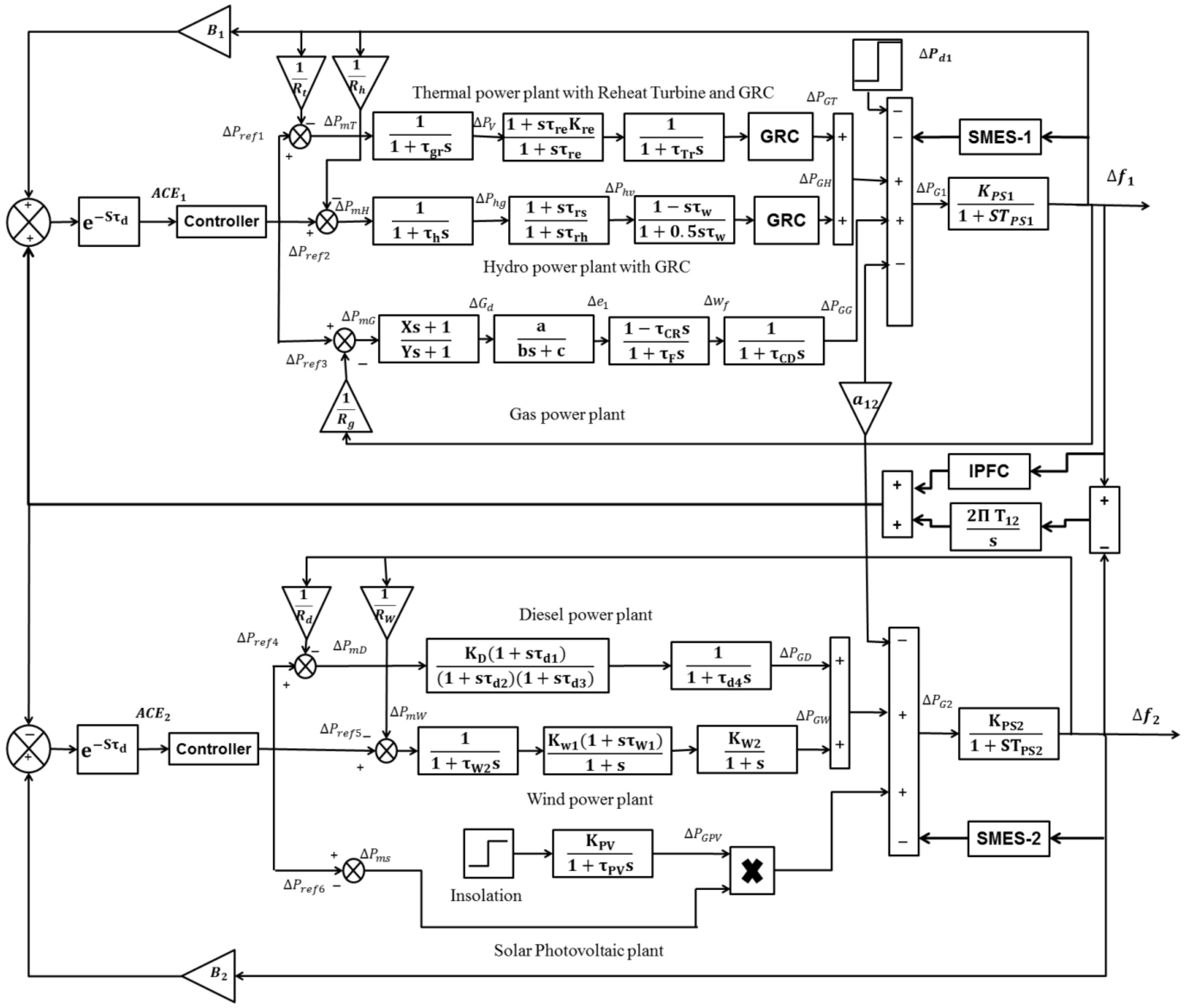


Fig. 1. Model of contemporary IPS considered for investigation.

In contrast to area-1, area-2 with 750MW total capacity incorporates renewable sources like solar photovoltaic penetration and wind unit along with a diesel plant. The contemporary IPS model comprised of RPGS is shown in Fig.1, and is developed in the domain of MATLAB/SIMULINK and the required parameters are chosen from [31-32]. The realistic constraint of limiting the real power generation raising and lowering that is GRC is perceived in this paper for both hydro and thermal units. Apart from that, the CTDs are perceived with the IPS model to establish the investigation nearer to realistic practice. The practical contemporary IPS is resided to a wide extent and employs many measuring devices located at remote points. The data from the device at a remote point is transmitted to the control centre to generate an error signal. The generated signal is received by the regulator in the plant location. The transmitting and signal receiving among various devices at different points will only take place with communication peripherals. Thus, communication peripherals inherit the time delay nature and these delays are playing their part in the performance of IPS. Due to the delay in signal transmitting and receiving there exists a delay in varying the generation. The operating point of the power system is altered regularly to keep the difference between real power demand and generation minimum. The real power mismatch is a direct analogy to the control area frequency and hence the stability. Thus, CTDs are needed to be confiscated at the time of regulator design. Transport type of CTDs are perceived in this paper and is modelled as [33]

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

3. Controller and Objective Function

The formulated problem in this paper is related to the control literature, thus the design of the FOPID regulator should follow the Caputo definition. Normally, the FO integral and derivative parameters are derived from FO differential equations subjected to initial conditions at zero. The FO integral-differential parameters for FOPID [34] regulator in this work are obtained from the derivative α^{th} of function f(t) is provided in (2).

$$D_t^{\alpha} f(t) = \frac{1}{\Gamma(m-\alpha)} \int_o^t \frac{D^m f(T)}{(t-T)^{\alpha+1-m}} dT, m-1 \prec \alpha \prec m \quad (2)$$

The modelling of FOPID is given in (3)

$$U_i(s) = K_P + \left(K_I / s^{\lambda} \right) + \left(K_D s^{\mu} \right) \quad (3)$$

The parameters are to be located optimally for better performance subjected to the index of integral square error (ISE) function in this work. ISE is more efficacious when it comes to the aspect of balancing peak minimization and settling time among other time-domain indices.

$$J_{ISE} = \int_0^{t_{sim}} \left(\Delta f_1^2 + \Delta P_{tie12}^2 + \Delta f_2^2 \right) dt \quad (4)$$

4. Superconducting magnetic energy storage

For the stability of realistic contemporary renewable-based IPS models, there will always be scope for the utilization of ESDs as territorial regulators. SMES is chosen to be incorporated with the investigative power system in this work on account of its efficacy and bulk storage capability when compared to other ESDs. The key components in the SMES device are power conditioning set up and coil wounded to the magnetic core. To attain superconductivity the wounded coil is maintained at cryogenic temperature, with this the conductor attains lossless nature. Usually, energy is stored in SMES at off-peak durations and delivered energy to the grid instantly whenever it has been required. The operation of SMES for storage purposes is noiseless, zero carbon emission and eco-friendly. The power conditional set-up in SMES regulates the energy storage and dissipation process concerning the deviation in control area frequency. Frequency deviation is correlated to real power mismatch, as the Δf in any control region falls behind the limits then instantly SMES injects energy to the grid to minimize the mismatch before the variation in power system operating point came into action. Modelling of SMES deliberated in this study is given in (5) and the time and gain parameters perceived are T_{SMES}=0.9972, and K_{SMES}=0.9080 respectively.

$$G_{SMES} = \frac{K_{SMES}}{1 + sT_{SMES}} \quad (5)$$

5. Interline Power Flow Controller

IPFC is one of the most dominant devices among all the available FACTs controllers. It employs several voltage source control units and is coupled to a common dc link. It can compensate for the flow of power in multiple transmission lines. Thus, to damp out the oscillations in tie-line power flow and to compensate for the line flow IPFC is integrated into conjunction with the line in this paper for LFC of the contemporary renewable-based IPS model. The architecture of IPFC deliberated in this paper is shown in Fig.2 [35].

Upon laying IPFC in conjunction with the line, the variation in tie-line flow is modelled as

$$\Delta P_{tie12}(s) = \Delta P_{IPFC}(s) + \Delta P_{tie12}^0(s) \quad (6)$$

The effect of IPFC on power flow in tie-line is given by

$$\Delta P_{IPFC}(s) = \left(K_1 \Delta f_1(s) + K_2 \Delta P_{tie12}^0(s) \right) * \left(\frac{1}{1 + sT_{IPFC}} \right) \quad (7)$$

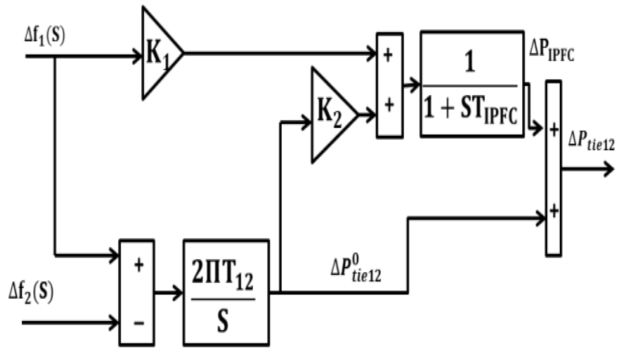


Fig. 2. IPFC architecture.

6. Water cycle algorithm

WCA is the modern optimization approach inspired by the process of the water cycle in nature and how streams and rivers finally fly into the sea in the practical world. The optimization process in this approach initiates with raindrops or snowdrops as initial particles. The emergence of snowdrops and raindrops in the mountain regions will flow downhill and forms streams or rivers. The formed stream or rivers flow downwards continuously and at last, merged with the sea. Here, the raindrops act as populations and the sea is the best solution. Here, in this paper, the WCA mechanism is implemented to find the gains of the FOPID regulator optimally. Hence, the raindrops are nothing but the parameters of the FOPID controller that are to be initiated randomly in an array as follows [36]:

$$RD_i = Y_i = [K_P, K_I, K_D, \lambda, \mu] \quad (8)$$

$$RD \quad Population = \begin{bmatrix} RD_1 \\ - \ - \ - \\ RD_i \\ - \ - \ - \\ RD_{N_{POP}} \end{bmatrix} \quad (9)$$

Later, the ISE index for every RD has to be evaluated using the equation provided in (10-11) and the positions of streams/rivers are initiated and subjected to the consideration of merging with the sea finally.

$$Position_{New}^{Stream} = Position^{Stream} + rand()* C * (Position^{River} - Position^{Stream}) \quad (10)$$

$$\mathrm{Position}^{River}_{New} = \mathrm{Position}^{River} + \mathrm{rand}()*C*(\mathrm{Position}^{Sea} - \mathrm{Position}^{River}) \quad (11)$$

The parameter 'C' value is assigned randomly from the range [0-2]. The process of evaporation and rain in WCA is modelled in equations (12-14).

$$|P_{sea} - P_{river}| < d_{max} \quad (12)$$

$$d^{new}_{max} = d_{max} - (d_{max}/\mathrm{max.iteration}) \quad (13)$$

$$P^{new}_{stream} = P_{sea} + \sqrt{U}\, X\, \mathrm{rand}(1, N_{var}) \quad (14)$$

The WCA algorithm procedural flow is rendered in Fig.3 and is developed in (.m format) in MATLAB to locate the optimal parameters of FOPID in this work for the LFC study of contemporary IPS.

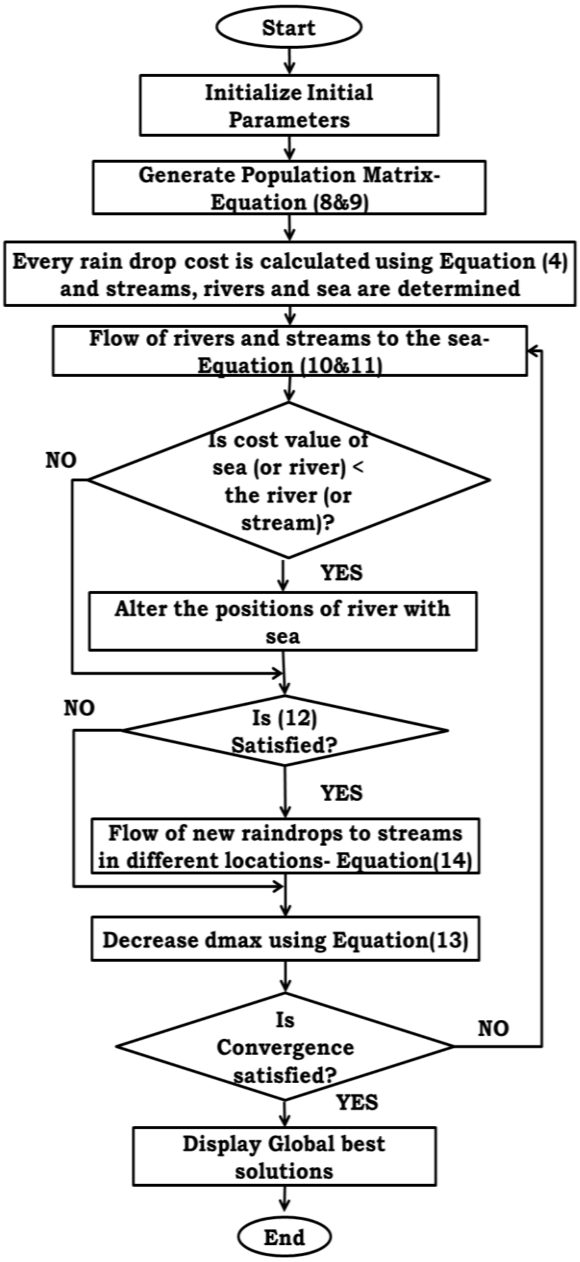


Fig. 3. WCA flowchart

7. Results and Discussion

7.1. Case-1: Analysis of contemporary IPS without considering CTDs.

Considered renewable energy sources based on contemporary IPS are investigated for 10%SLP disturbance on area-1 and the constraint of CTDs is not taken into account. Regulators of FOPID, PID and PI are placed in each control area one by one and are rendered optimally using the nature-inspired optimization technique of WCA. Dynamic responses of contemporary IPS under various regulators are compared in Fig.4, and the responses with FOPID are shown to be more enhanced in the aspects of both settling time and peaks overshoot/undershoot diminishing. Moreover, the ISE is improved and is greatly minimized with FOPID compared to others and is enhanced by 71.875%with PID and 88.30%with PI. Responses settling time in seconds are noted in Table 1 and the corresponding controller optimum gains are noted in Table 2.

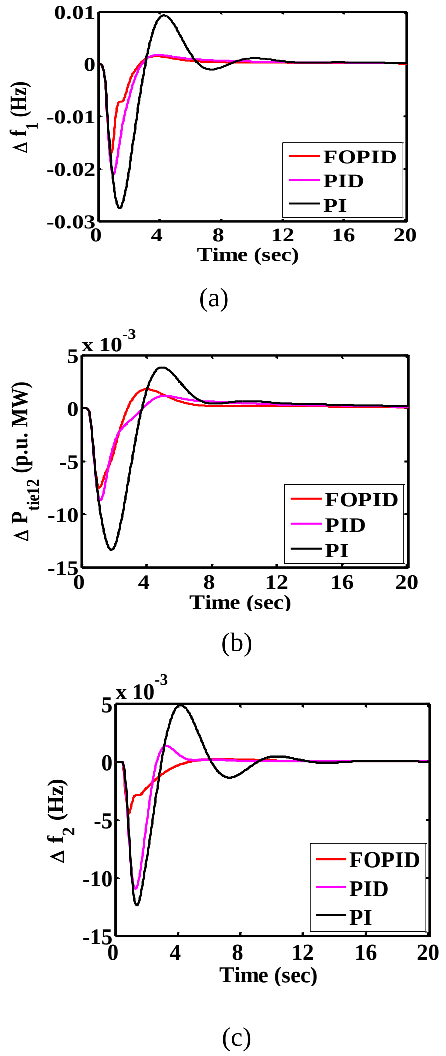


Fig. 4. Case-1 Responses. (a).Δf_1, (b).ΔP_{tie12}, (c).Δf_2.

Table 1. Responses settling time under various cases.

Controller	Case-1				Case-2			
	Δf_1	ΔP_{tie12}	Δf_2	ISE $*10^{-3}$	Δf_1	ΔP_{tie12}	Δf_2	ISE $*10^{-3}$
PI	12.27	15.13	11.90	22.32	21.77	22.39	14.96	72.83
PID	10.09	12.24	8.64	9.28	13.57	14.35	13.02	29.36
FOPID	7.98	8.25	7.67	2.61	11.261	11.22	9.388	13.68

Table 2. Controller optimal gains.

Parameters	Case-1			Case-2		
	PI	PID	FOPID	PI	PID	FOPID
Case-1	K_P=0.996 K_I=0.042	K_P=0.835 K_I=0.125 K_D=0.448	K_P=0.308 K_I=0.198 K_D=0.188 μ=0.558 λ=0.450	K_P=0.896 K_I=0.102	K_P=0.678 K_I=0.251 K_D=0.484	K_P=0.411 K_I=0.201 K_D=0.199 μ=0.672 λ=0.542
Case-2	K_P=0.975 K_I=0.073	K_P=0.868 K_I=0.220 K_D=0.268	K_P=0.291 K_I=0.098 K_D=0.367 μ=0.431 λ=0.406	K_P=0.798 K_I=0.094	K_P=0.796 K_I=0.218 K_D=0.309	K_P=0.398 K_I=0.316 K_D=0.298 μ=0.562 λ=0.497

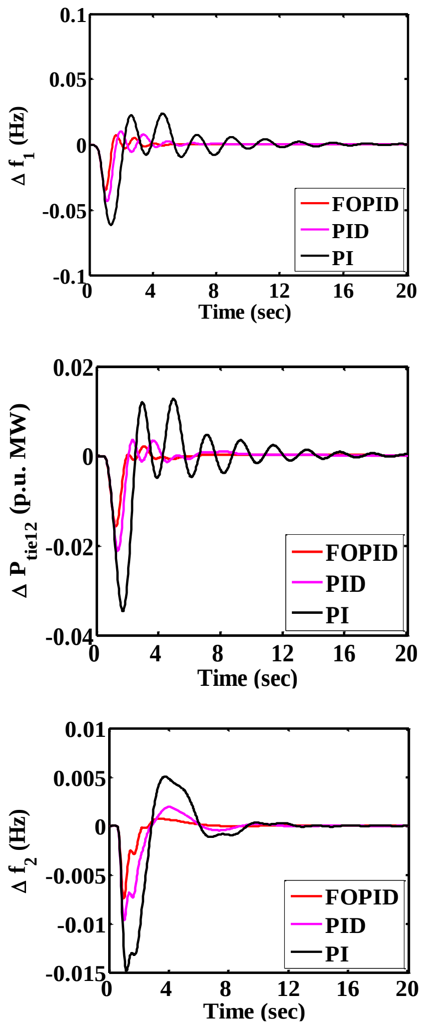
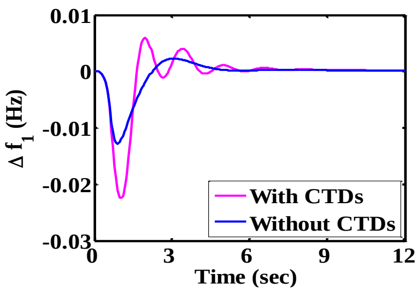


Fig. 5. Case-2 Responses. (a).Δf_1, (b).ΔP_{tie12}, (c).Δf_2

7.2. Case-2: Analysis of contemporary IPS with considering CTDs.

The practical constraint of CTDs is considered with renewable-based contemporary IPS in this case for the identical disturbance in a load of 10%SLP. Responses of considered IPS under various regulators are compared in Fig.5 and is concluded primarily that FOPID dominates the performances of PID and PI. Even though the contemporary IPS is conceived with CTDs, FOPID showcases its supremacy in handling the deviations to reach a steady condition in a quick time. Thus, WCA based FOPID is declared the best compared to other IO type classical controllers. The additional parameters in FOPID provide better regulation in damping out the oscillations and further the ISE for FOPID is strengthened by 81.216%with PI and 53.405% with PID.



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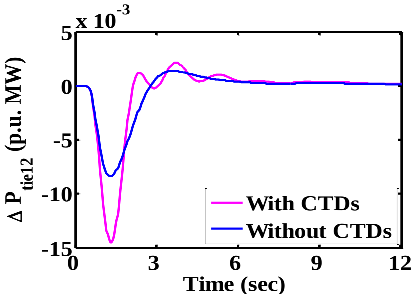

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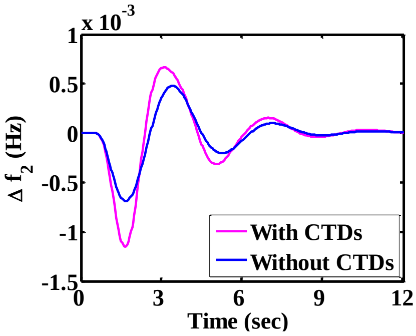
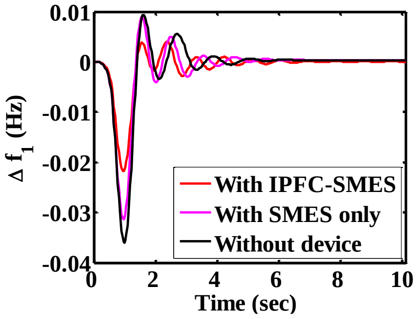


(c)

Fig. 6. Case-3 Responses. (a).Δf_1, (b).ΔP_{tie12}, (c).Δf_2.

7.3. Case-3: Demonstrating CTDs impact on performance of contemporary IPS.

From the above analysis, it has been concluded that the WCA based FOPID is more efficacious. Hence responses of contemporary renewable-based IPS with and without CTDs under FOPID are compared in Fig.6 to show the impact of CTDs. Noticing from Fig.6, that responses of contemporary IPS including CTDs are exhibiting more deviations in the frequency of control area-1 (Δf_1), control area-2 (Δf_2) and tie-line power (ΔP_{tie12}) compared to the situation of not including CTDs with the system. This means there will be a definite time lag in signal transmitting and receiving within different devices located at faraway points via communication channels. With these delays, there will be a lag in the command signal from the control centre to the controller at the plant site. Thus, the necessary action performed by the regulator in changing the power system operating point is performed with some delays. The mismatch in real power may even get worsened due to these CTDs thereby affecting the IPS performance. Despite more deviations in responses of IPS considering the CTDs, the designed regulator drags the deviations to steady conditions. Thus, this paper recommends CTDs consideration with IPS models in the study of LFC while developing the secondary regulator. The delay in the time of 0.12 seconds is considered in this work which is a realistic one. It is noteworthy that performing the LFC analysis on IPS models without addressing the CTDs effect of the designed regulator may not yield beneficial results in case of unpredictable delays emerging within the system.



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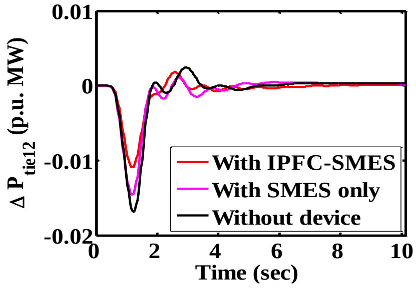

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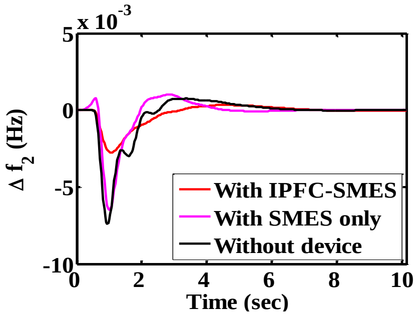

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Fig. 7. Case-4 Responses. (a).Δf_1, (b).ΔP_{tie12}, (c).Δf_2.

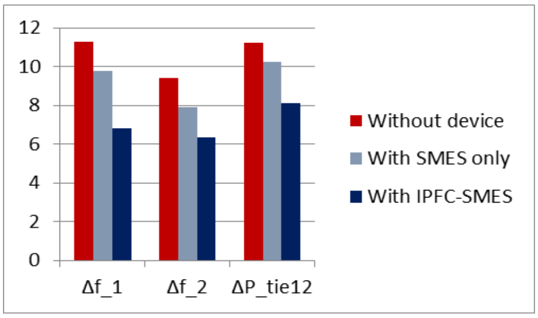


Fig. 8. The bar-chart represents settling time in seconds (on the Y-axis) for Case-4.

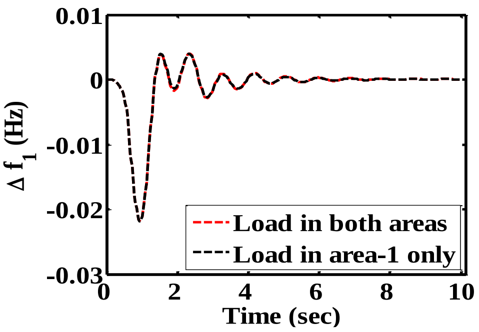
7.4. Case-4: Analysis of contemporary IPS with considering CTDs under coordinated IPFC-SMES strategy.

To overcome the subsidiary deviations that had occurred in the system performance while considering CTDs, it is adequate to implement the territorial strategy. In this work, initially, the renewable-based considered contemporary IPS is incorporated with SMES in each area and the behaviour of the system under load disturbances is analysed. Later, IPFC is incorporated in conjunction with AC tie-line along with

SMES in both the areas and the responses are compared in Fig.7. Observing Fig.7 concluded that on implementing the strategy of SMES-IPFC there exists a considerable enhancement in IPS performance. IPFC works more efficacious in damping out inter-area oscillations and SMES facilitates a considerable shrink in deviations of respective control area frequency. The settling time of IPS responses is indicated in the form of a bar chart in Fig.8, for easy interpretation.

7.5. Case-5: Sensitivity test.

The suggested WCA optimized FOPID regulator in coordination with the territorial strategy of SMES-IPFC in renewable sources based contemporary IPS is targeted with loadings in both the areas and also with random loading in area-1. The IPS responses for loading in both the areas are rendered in Fig.9, and random loadings it has been depicted in Fig.10. From sensitivity analysis, it has been observed that the deviations in IPS responses are not seen much even though the system is loaded in both areas. Moreover, with the effective strategy of SMES-IPFC, the performance of the IPS looks more stable even if it is subjected to random loadings. Thus, FOPID based on WCA with SMES-IPFC territorial strategy presented in this paper is robust.



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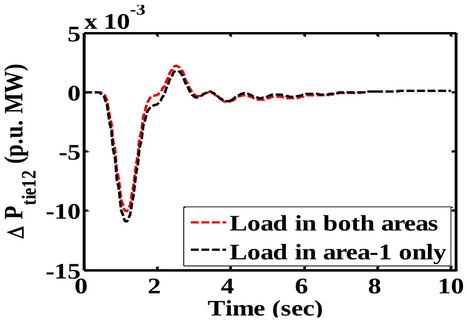

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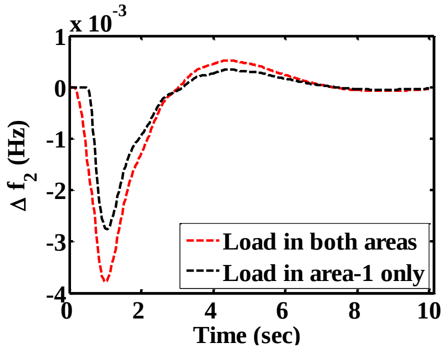
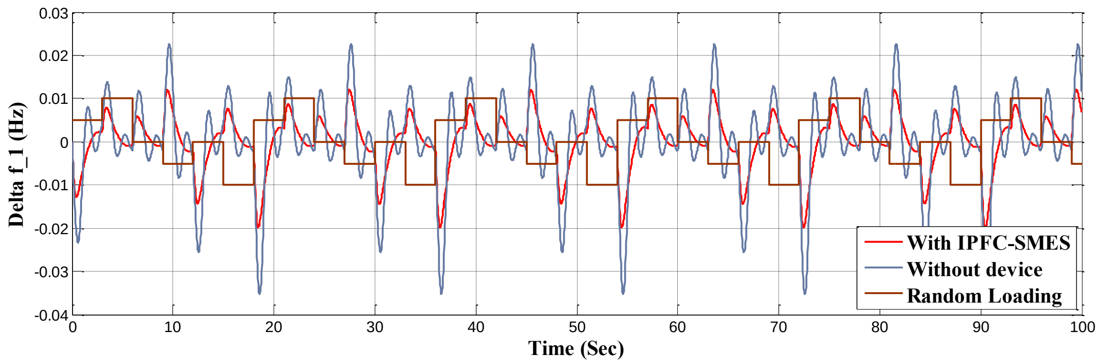


(c)

Fig. 9. Case-5 responses with load in both the areas. (a).Δf_1, (b).ΔP_{tie12}, (c).Δf_2.



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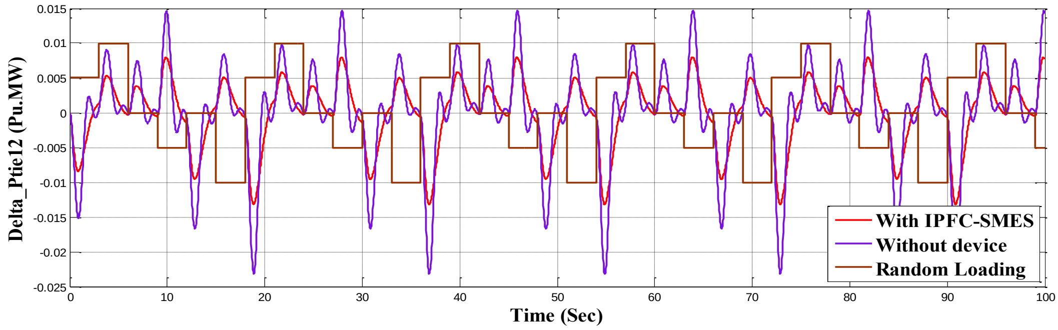

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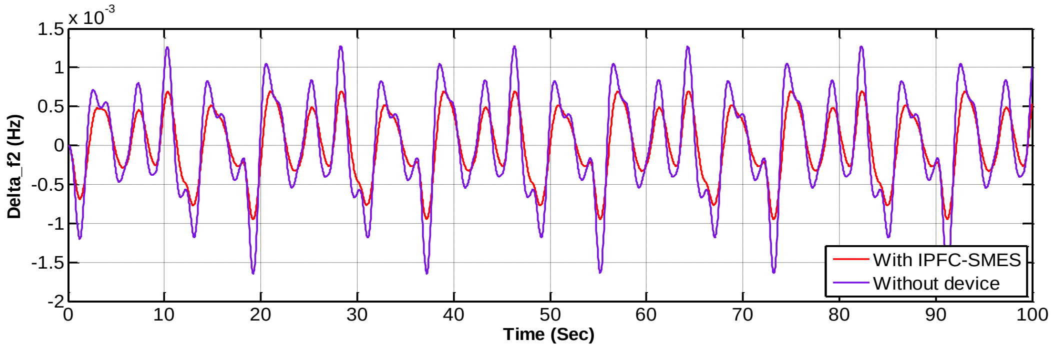

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Fig. 10. Case-5 responses with random laoding.(a).Δf_1, (b).ΔP_{tie12}, (c).Δf_2.

8. Conclusion

WCA tuned FOPID is implemented successfully for renewable sources based on contemporary IPS in the LFC study. Efficacy of FOPID is showcased with PI, PID conventional regulators. The test system is perceived with CTDs in the vision of performing analysis in more practical aspects. The dynamic behaviour of the investigative system has been analysed with and without considering CTDs to showcase its impact. Simulation results reveal the significance of CTDs on power system performance. With CTDs the system responses are slightly deviated more and also concede more time to settle down because of the delay in delivering the control signal to the generators to alter the operating point. This paper suggests considering test system models with CTDs to avoid the chances of instability due to unexpected time delays. Later, SMES-IPFC coordinated strategy is implemented in the contemporary IPS under WCA based FOPID regulator. Test system responses reveal the enhancement in dynamic behaviour with SMES-IPFC devices under the same perturbed conditions. Robustness of FOPID along with SMES-IPFC coordinated regulation is revealed with random loadings of sensitivity analysis.

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