A PSO Based Modified Multistage Controller for Automatic Generation Control with integrating Renewable Sources and FACT Device

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Abstract- This study focuses on modelling of two area hydro-thermal interconnected system integrated with wind, Small Hydro Plant (SHP) and Solar Thermal Plant (STP). Flexible AC Transmission (FACT) device named as Static Synchronous Series Compensator (SSSC) and an energy storing element called Super Magnetic Energy Storage (SMES) unit is incorporated in the model. To control and monitor the test system, an effective Particle Swarm Optimization (PSO) optimized multistage controller is proposed. The proposed controller parameters are optimized through PSO technique. The effectiveness of the suggested controller is verified under diverse step and time varying load perturbation. The superiority of controlling action of the proposed controller is also proved to be efficient than other prominent controllers. System stability is analysed and found to be stable through the establishment of Eigen value analysis and bode plot. Furthermore, the system behaviour is studied with various combinations of SSSC and SMES in different area simultaneously. To make the analysis more realistic, appropriate time delay is included in the proposed study. Finally, sensitivity analysis of the network by varying the different system parameters, governed through a multistage controller is carried out.

Keywords Automatic Generation Control; Particle Swarm Optimization; Solar Thermal Plant; Static Synchronous Series Compensator; Super Magnetic Energy Storage.

1. Introduction

A reliable power network is characterized by its associated system constraints and depends upon successful control strategies for economical operation. With regard to that, AGC is one of the effective strategies which need to be reflected in the power structure for deriving output. The prime objective for including AGC in the power system is to maintain the frequency deviation within the prescribed limit and regulate the incremental power change in tie line called as tie line power at scheduled level. Normally in the present scenario, electrical energy is harvested form conventional power plant such as thermal and hydro. Also literatures survey [1-3] revels that, most of the works performed in the field of AGC study for an interrelated power system is focusing on various combinations of thermal and hydro units. Moreover, the transfer function of hydro turbine is not same as of thermal as it holds non-minimum phase characteristics and make the design of hydro plant different to thermal. Apart from these, integration of renewable power plant like wind, CSP and SHPP with the grid, make the whole system more reliable. Normally, renewable power plants are used as peak load power plant [4]. Therefore, the effect of renewable power plant on the system behavior with concerning to AGC need to further explored. After pioneering work done by Elgerd et al. [1] in the field of AGC, Nanda et al. extends the AGC work to two area hydro-thermal system by considering the nonlinearity i.e. GRC [2]. The same author also carried out the study with three area system using GRC and reheat turbine. Later Saika et al. have performed analysis on two area system as well as three and five area unequal system incorporating various non-linarites [3].

Due to carbon emission from fossil fuel burning plants and its hazardous impact on environment, it is urgency to adopt renewable based power plants. SHP is a clean, economical and low investment renewable based power plant and gaining popularity day by day. Dolla et al. used this high efficient plant in the area of load dumping by regulating water pressure in connecting tubes [4]. The mathematical representation of SHP in terms of transfer function is presented by Fan et al. [5]. The author in [5], also analyzed the frequency deviations and tie line power with considering only SHP. After that, Sharma et al., performed the AGC study considering SHP along with other power plants [6]. Another renewable power plant STP plays a prominent role in power generation [20]. The concept of STP in AGC is laid by Das et al. but the study is limited to isolated mode only [7]. Sharma et al. investigated three area AGC system with STP and applied different control strategies [8]. Researchers also compared the three area system considering STP and other generating units. The technology involved in the wind power plant is matured and proven to be effective under sudden disturbances like wind speed variation. Kumar et al. examined the two area AGC model concentrating on hydraulic pitch actuator wind turbine generator with data pitch response combined with the energy storage system [9]. Complex power system demands modern and advance power electronics switches and equipment's like FACTs devices and energy storage system. These systems not only enhance the power transfer capabilities of interconnected power system but also improve the system stability. Some of well-known FACT devices are Static Synchronous Series Compensator (SSSC) [9–10], Thyristor Control Series Capacitor (TCSC) and Interline Power Flow Controller (IPFC) which are widely used in power network to effectively coordinate the real power movement in the transmission line. Similarly, some of well appreciated energy storage devices are Ultra Capacitor (UC), Battery and SMES [10]. The storage system actively supports the system stability by injecting the active power into the grid and thereby adding the storage capability to further level [21, 24].

To effectively monitor and regulate the interconnected complex power system, an efficient controller is needed. As per the modern control theory, various controllers like Integral (I), Proportional Integral (PI), PID, Fractional Order PID (FOPID), and Cascaded controllers are used by various researchers. Moreover, tuning of controller parameter is one of the significant tasks for efficient operations [21]. Ali et al. used BFOA algorithm to tune the PID controller and the response is equated with that of ZN and GA algorithm [11]. Sahu et al. used same PID controller but the parameters are tuned through hybrid firefly algorithm [12]. Parmar et al. presented a multi-area system and used only output state variable for controlling the system [13]. Sanki et al. used PSO algorithm to tune the controller of renewable based generator [14]. Dash et al proposed a new type of controller i.e PD-PID controller optimized through bat optimization technique and PI-PD controller optimized by flower pollination algorithm [15].

It is observed from the literatures that, most of the researchers used single controller in the study and few papers presents the concept of multistage controller that are used in conventional system. Hence further analysis in multistage controller need to be investigated. Apart from this, a realistic system should be incorporated various non-linarites in the system and renewable based plants [23]. During the literature survey of AGC revealed that, vary few researchers analyzed the system containing renewable energy sources with non-linearity (GRC). Hence authors attempt to study the system incorporating renewable energy sources like wind, SHP and CSP with GRC, effectively controlled through the proposed controller. Furthermore, the system is analyzed with FACT device i.e SSSC and energy storage system i.e SMES. The behavior of system response is also studied with different loading conditions and the result is equated with a recent literature [14]. The work presented in this paper is briefly underlined by the following points.

- Design and development of two area hydro thermal system with renewable energy sources incorporating SSSC and SMES.
- Modelling of multi stage controller and tuning the controller parameters through PSO algorithm.
- To study the effect of SMES, SSSC and time delay with proposed controller.
- To analyse the system stability through Eigen value and bode plot along with diverse step load perturbation and time varying load perturbation.
- To check the robustness (sensitivity) of system by changing system parameters.

The basic layout of the current paper as follows: after short introduction, the system modelling is described in section 2. The detailed design of the proposed controller with the mathematical expression is presented in section 3, followed by PSO optimization algorithm in section 4. The system behavior subjected to step load perturbation, time varying load disturbances, time delay, change in solar irradiances and stability of the system is discussed in section 5. Finally, the concluding remark of the study is given in section 6.

2. System Modelling

The proposed study contains two interconnected area and both the area are linked through a transmission line called tie line in which power exchange takes place between the area. Thermal and hydro units are present in both area-1 and area-2. Thermal power plant contains hydraulic amplifier and non-reheat turbine [12]. Similarly, the hydro unit contains hydro speed governor, its associated turbine and non-linearity (GRC) as shown in Fig. 1. To make the system further realistic, various renewable based power units such as wind, STP and SHP are included in both the area as shown in Fig. 1. With advancement of renewable energy, the dependency on fossil fuel based conventional power plant is greatly reducing for generation of electricity. In recent years, wind power plant emerging new sources of power generation as it produces environment friendly power. The wind power plant considered in the study contains hydraulic pitch actuator and data fit response with the blade characteristics [9]. The detailed transfer function is shown in Fig.1. It is also observed that, SHP becoming more popular in recent years, both in economic criterion and renewable energy source. It can also be used with AGC, thereby realizing the concept of smart grid [5]. In general, SHP contains generator, turbine and a speed regulator [6].

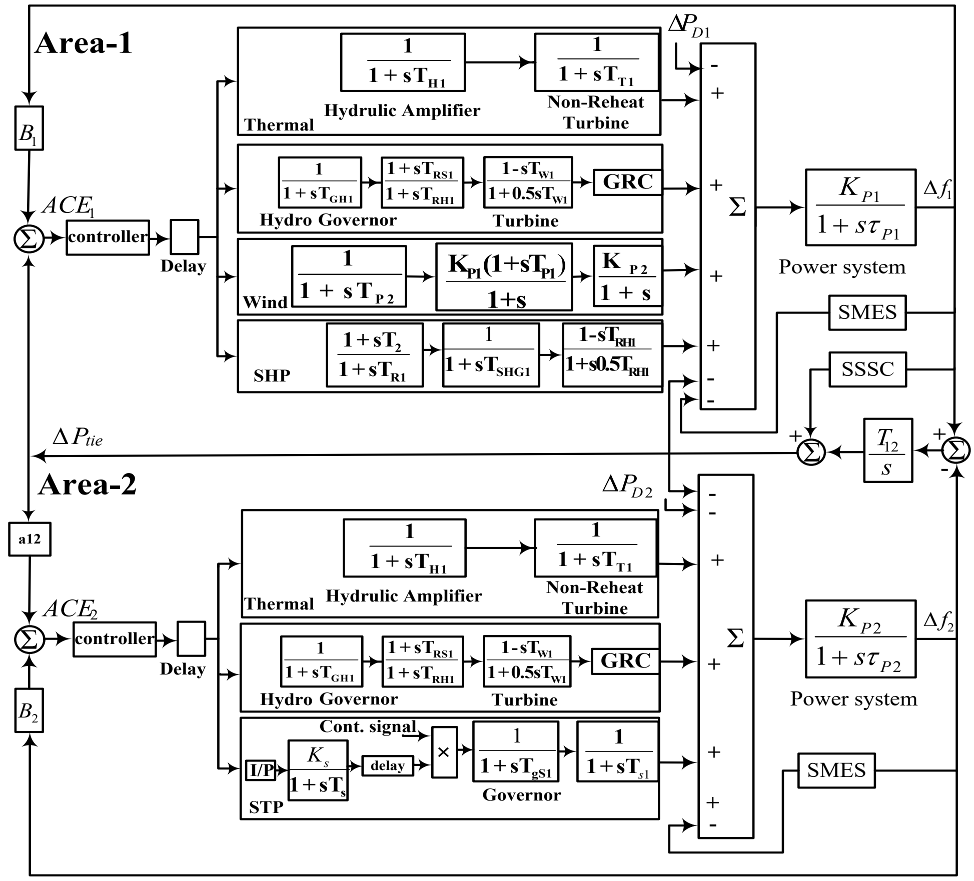


Fig. 1. Block diagram of multi area test system.

In today's world, solar energy has great importance than other renewable based power unit and growing rapidly across the globe even in outside as used in satellites for powering. STP contains large collector used for focusing the solar irradiance into pipes contains heat absorbing fluid such as water or molten salts [7]. STP used in the study contains solar field, turbine and governor as presented in Fig. 1. Delay of 1 sec. is considered in STP design for involving various operations. There are two inputs in STP named as controller inputs and solar irradiance as shown in Fig.1 .Usually, SMES is used as an energy storage system to damp out the oscillations through its fast acting mechanism.

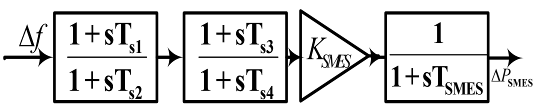


Fig. 2. Modelling of SMES

It removes the frequency oscillation caused by load variation by supplying the active power stored in the magnetic field of SMES [9]. Overall, it enhances the system stability for a short duration until the controller takes corrective measure to restore the power system. The mathematical modelling of the SMES unit is shown in Fig. 2. SSSC is a member of FACT devices used as a frequency stabilizer, connected in series with tie line. The equivalent mathematical modelling of the SSSC is shown in Fig. 3. It offers inductive plus capacitive reactance to transmission scheme. Therefore, SSSC can normalize and adjust the dynamic power flow, so that power carrying capacity of the transmission line increases. The prime objective of using SSSC is to reduce the oscillations present in the transmission line [10].

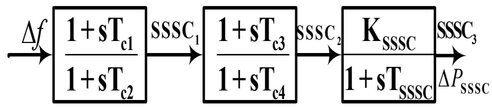


Fig. 3. Modelling of SSSC

The arrangement of SSSC comprises of proportional gain with the combination of proper phase lag–lead compensating block to provide required phase delay between input and output.

3. Proposed Controller Design

With expansion of the energy sector with integration of renewable energy, the objective of maintain the system stability as well as reliability is also essential. Hence an effective controller design is necessary. In this context, most used controller in the field of AGC study is PID controller which still remains effective, simplest, and easily operative controller structure [11].

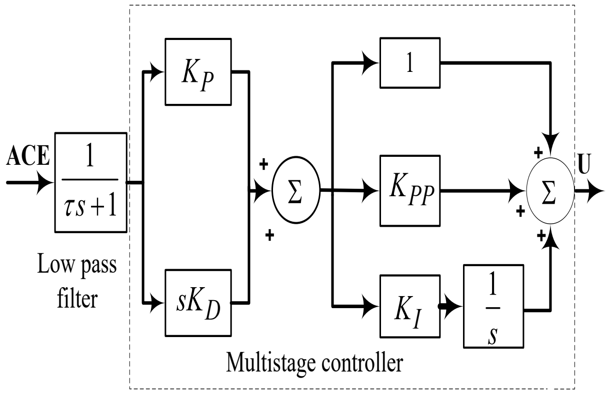


Fig.4. Block diagram representation of proposed controller

Although the PID controller is simple to implement but unable in producing improved response with respect to transient and steady state [22]. Moreover, with increase in proportional gain which reduces the steady stare error and the response further deteriorates in transient state [19]. Also high gain value of proportional term slow down the speed of the system and stability during the transient state. So to improve the performance in the transient state, the effect of proportional action should be minimized [15]. This can be achieved through multi stage i.e. (PD)-(1+PI) controller, in which first stage contains PD controller and second stage contains 1+PI controller [16]. The transfer function of this arrangement is depicted in Eq.1.

$$T.F_{multistage} = (K_P + sK_D) \times (1 + K_{PP} + K_I/s) \quad (1)$$

Multistage control method is one of the suitable methods used for enhancement of the system response [8]. This arrangement ensured the system stability during the load disturbances as it has more number of tuning knobs compared to a conventional controller. Keeping view of above advantages, many researchers used this type of controller arrangement in their research area. The overall diagram of multi stage controller is shown in Fig. 4. In AGC, several sensors are used to sense the various parameters, which produce the noise in the system. Tie line telemetry system also adds the noise further. If the noise persist longer duration, it may lead to malfunction of the controller and other sensitive equipment. Hence the high frequency noise signal should be eliminated by using an additional filter [17]. Hence in the system, a 1st order low pass filter is considered in the multistage controller as shown in Fig.4 and the transfer function is depicted in Eq. 2.

$$TF_{filter} = \frac{1}{\tau s + 1}; \|\tau\| << 1 \quad (2)$$

The effectiveness of the filter can be varied by changing the value of τ. However, insufficient filtering can be occurred if τ value assumed to be too small. Therefore the optimum value of τ is selected by appropriate tuning which is usually several times less than the lowest frequency deviation [17]. For our study the value of τ is assumed to be 0.1sec. For the fine-tuning of the controller variables through optimization technique, generally a cost function is used. There are various cost function used in AGC study named as Integral of Time multiplied Absolute Error (ITAE), Integral of Squared Error (ISE), Integral of Time multiplied Squared Error (ITSE) and others. Numerous studies show that ITAE offers better result with respect to overshoot/undershoot and settling time than other integral based performance criteria [13]. Hence, ITAE is chosen as cost function in this study and represented in Eq.3, in which Δf_1 and Δf_2 are the frequency deviation and ΔP_{tie} is the change in power in tie line. The maximum and minimum values of the controller parameter are the constraints of the cost function.

$$J = \int_0^{t_{sim}} t \times \left(\left| \Delta f_1 + \Delta f_2 + \Delta P_{tie} \right| \right) \quad (3)$$

4. PSO Optimization Technique

PSO is one of the renowned stochastic optimization methods which use the social behavior for exploration of optimum solution in the solution space. With advancement, lots of emerging concepts have been applied in PSO which are not present in the traditional PSO algorithm proposed by Kennedy et al. [18] for obtaining better result in the solution region in various research fields. However, the basic design principle remains same throughout the process in the design. Let us consider the mathematical modelling of PSO for an N-dimension search space, the m^{th} particle is denoted as $X_m = [x_{m1}, x_{m2} \ldots x_{mn}]$ and the best value for the best particle is denoted by "g". $P_m = [p_{m1}, p_{m2} \ldots p_{mn}]$ are the best previous position of the m^{th} particle and the change of position is evaluated through velocity represent as $V_m = [v_{m1}, v_{m2} \ldots v_{mn}]$. In each iteration of the algorithm, the particle position is assessed by adhering the following equations.

$$V_m^{i+1} = wV_m^{i+1} + c_1 r_{m1}^i (P_m^i - X_m^i) + c_2 r_{m2}^i (P_g^i - X_m^i) \quad (4)$$

$$X_m^{i+1} = X_m^i + V_m^{i+1} \quad (5)$$

Where i=1,2,…..Z , Z represents total number of population, w represents inertia weight while c_1 and c_2

represents the cognitive and social parameter respectively. Two random numbers i.e. r_{m1} and r_{m2} are used in the Eq. (4) and ranges in between 0 and 1. To update the velocity of the m^{th} particle Eq. (4) is used while Eq. (5) is used to evaluate the position of each particle by adding the new velocity found on Eq. (4) with current position X_m. The movement of each particle is controlled through these two equations with subjected to a function which repeatedly calculates the fitness of the population. The fitness function calculates how far or near the solution is from optimum solution. Therefore, the movement of each particles can be adjusted so that it satisfy the performance criteria decide by objective function, means the derived solution reach the target as close as possible. At each iteration, PSO algorithm relies on fitness function and velocity update for its effectiveness [20]. Hence selection of objective function according to performance criterion is crucial in the exploration course of optimization algorithm. For better understanding of the whole PSO algorithm, the pseudo code is shown below.

Initialize the size of population, static and dynamic parameter

do

For each paricle P with position X_P , follow the steps

If (fitness $f(x_P)$>$Pbest_P$)

Keep $Pbest_P$ and discarded x_P

endif

endfor

Define best solution $gbest_P$ which is neighbor of P

For each particle P repeat following steps

Calculate velocity and position by using Eq. (4) and (5)

endfor

While *(max. iteration reached or stopping criteria met)*

5. Result and Discussions

In this section, the brief discussion on system stability and system performance of two area renewable based power network is presented. To regulate the system, PSO tuned multistage controller is used and its boundary condition is defined as 0< K_P, K_D, K_{PP}, K_I < 3. The values of multistage controller in both areas are presented in Table 1. The suggested multistage controller is modelled and successfully used in the projected system through MATLAB software.

5.1. Stability Analysis

Stability analysis of various methods such as bode plot (phase margin and gain margin) and Eigen value analysis of the proposed model is presented in this section. Eigen value is calculated by using Eq. (6) and (7). Where, A represents the system matrix and I is the identity matrix. Eigen value is represented by λ and its real and imaginary part is denoted by α and β respectively. All Eigen values and its corresponding damping ratio (ζ) and frequency of oscillation (ω_n) are shown in Table 2.

From the concept of control theory approach, it is known that for a stable system, all the Eigen values must have negative real part and one zero Eigen value with geometric multiplicity equal to algebraic multiplicity. Geometric multiplicity is the dimension nullity in the matrix (A-λI) and algebraic multiplicity is defined as numbers of occurrence of an eigen value in origin. The response of bode plot (Fig.5) is also smooth even the model is highly complex. Therefore, by referring Table 2 and Fig.5, it is concluded that the system is stable.

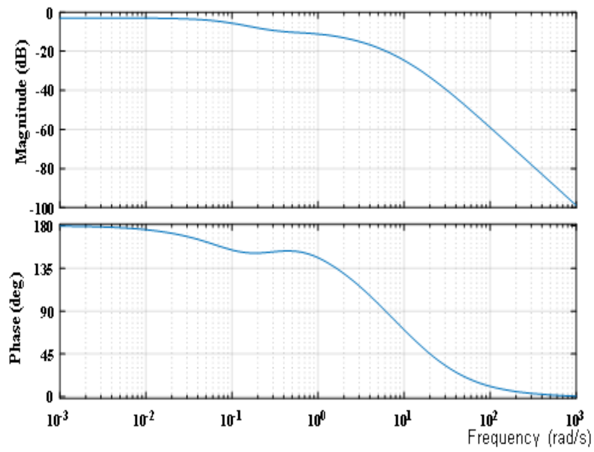
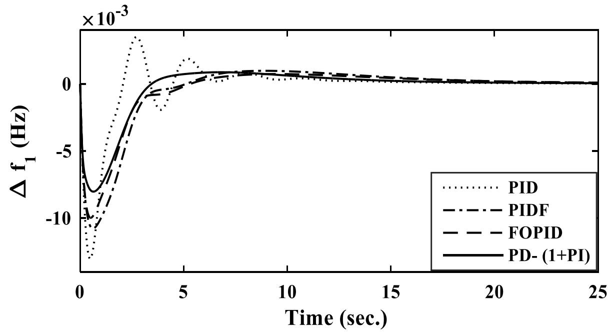


Fig. 5. Bode plot of the 2-area system

5.2. Performance Analysis

The suggested multistage PSO tuned controller is used in the system to control and monitor the frequency change and variation in tie line power. The effectiveness of the multistage controller is equated with the well-known other controllers like FOPI, PIDF and PID controller scheme. The superiority of the proposed controller over other controller is displayed in Fig.6 and associate mathematical parameters i.e peak over/under shoot (OS/US) and settling time (Ts) are presented in Table 3.



(a)

Table 1: Various parameters of the proposed controller

Controller / Optimization technique		Controller Parameters				Obj. fun (ITAE×10^{-2})
		K_P	K_D	K_{PP}	K_I	
Area-1	PD-(1+PI) :PSO	1.184	1.781	2.351	2.174	1.5254
Area-2	PD-(1+PI) :PSO	1.054	1.619	2.636	2.284	

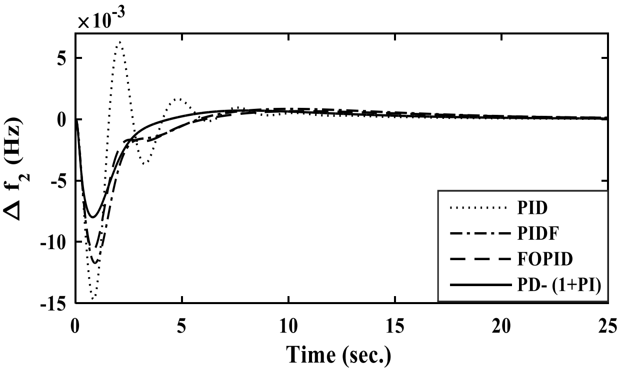
Table 2: Eigen value analysis of proposed system

Eigen values	Min. value of damping ratio	Min. value of Freq. of oscillation (Hz)
-0.0010, -0.0002, 0.0200, -4.3905, -4.3916, -4.3913, -4.3905 ,-0.3644, -0.1336 ±j 0.1353, -0.3337, -0.1932, -0.3333,-0.0756 ± j0.0288, -0.0681, -0.0656, -0.0409, -0.0368, -0.0173 ± j0.0209, -0.0111 ±j 0.0124, -0.0111 , 0, -0.0084 ± j0.0021, -0.0021 ±j 0.0022, -0.0027 ± j0.0015, -0.0020, -0.0003 , -0.0003 ± j 0.0005, -0.0033, -0.0056,-0.0100, -0.0056 , -0.0033, -0.0100, -0.0676 , -0.0125	0.5144	0.02

Table 3: System performance for various controller

Controller	Δf_1		Δf_2		ΔP_{tie}	
	OS/US (×10^{-3})	Ts (sec) (2%)	OS/US (×10^{-3})	Ts (sec) (2%)	OS/US (×10^{-3})	Ts (sec) (2%)
PD-(1+PI)	-8.015	17.83	-7.916	17.16	-2.511	22.68
FOPI	-9.934	17.92	-10.92	17.59	-3.225	22.97
PIDF	-10.87	18.31	-11.87	17.96	-3.469	23.18
PID	-13.26	18.69	-14.83	18.29	-4.387	23.66

The system is further investigated to analyse the effect of SSSC and SMES on the model behaviour. The graphical representation is shown in Fig. 7 and mathematical data is also recorded in Table 4. For better understanding, without SSSC and SMES is denoted as case-I, SMES in area-1 as case-II, SMES in area-2 as case-III and with SMES and SSSC in system as case-IV. To prove the effectiveness of the controller, the result is compared with that of similar work carried out by Sanki et al. [14] and the compared mathematical indices are shown in Table 4.



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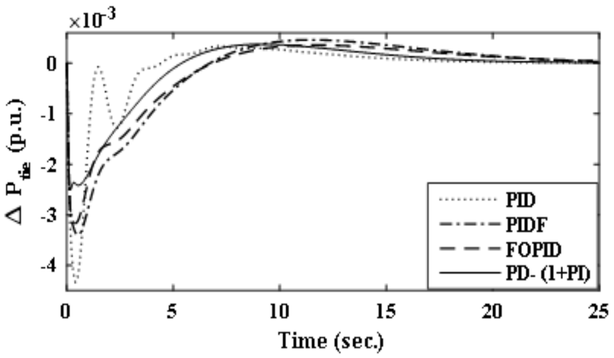
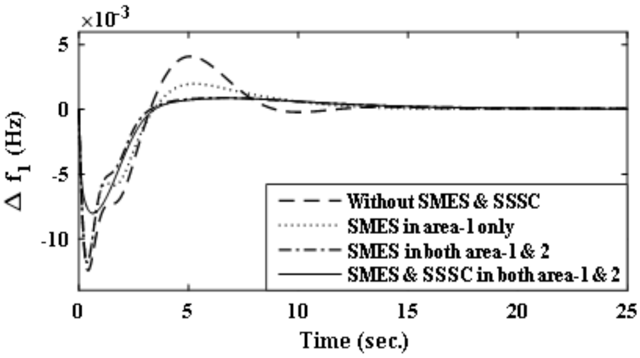
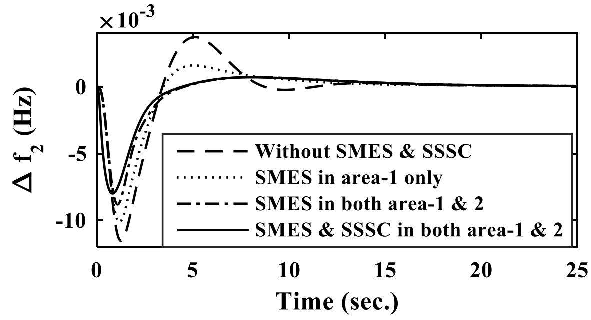


(c)

Fig. 6. Response for (a) freq. deviation in area-1 (b) freq. deviation in area-2 and (c) tie line power change for SLP of 1% in area-1 with various controllers



(a)



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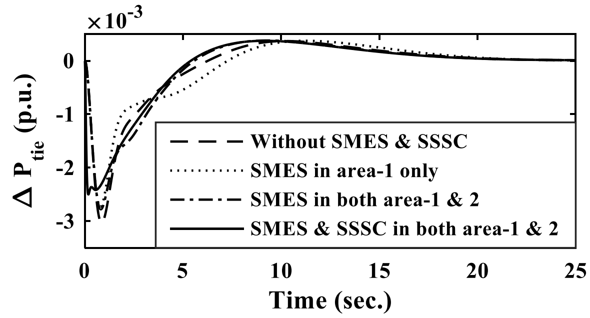
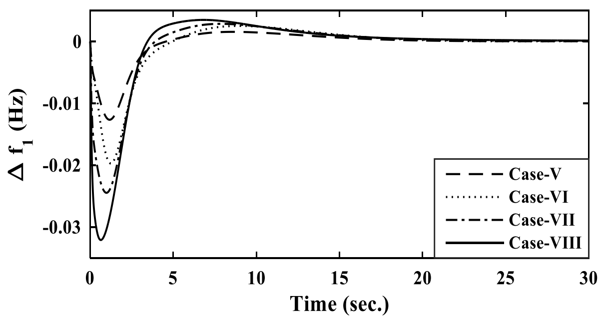


(c)

Fig. 7. Response showing the effect of SSSC and SMES (a) freq. deviation in area-1 (b) freq. deviation in area-2 and (c) tie line power change for SLP of 1% in area-1.

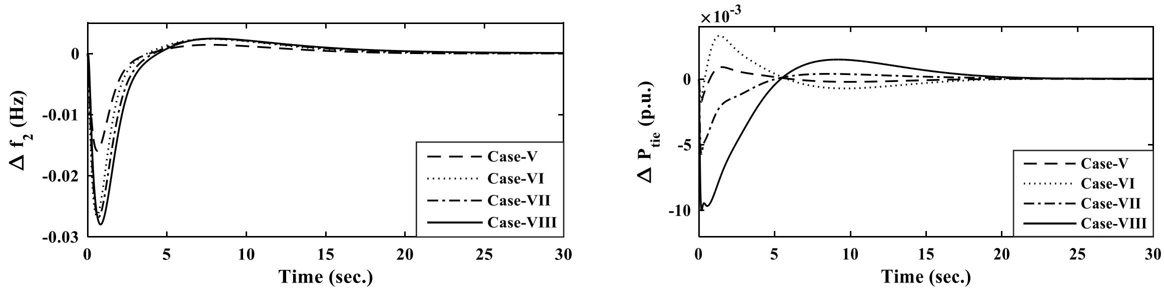
. Again the proposed controller is found to be efficient subjected to various step load perturbation such as: Case V: SLP of 1% in both area-1 and 2, Case VI: SLP of 1% in area-1 and 2% in area-2. Case VII: SLP of 3% in area-1 and 1% in area-2.Case VIII: SLP of 5% in area-1 only. The parameter of case V, VI, VII and VIII presented in Table 4 and its graphical representation is shown in Fig. 8. Moreover the outcome of time delay on the model response is presented in the Fig. 9. For verifying the robustness of the system, sensitivity examination of the test model is investigated by fluctuating the time constant of governor (T_g), turbine (T_t) and the synchronizing time constant (T_{12}). The measured response is shown in Fig. 10.



(a)

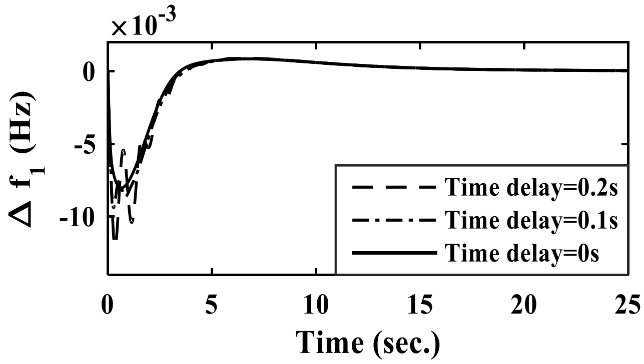
Table 4: System performance indices for various conditions

Case/controller		Δf_1			Δf_2			ΔP_{tie}		
		US ($\times 10^{-3}$)	OS($\times 10^{-3}$)	Ts (s.) (2%)	US($\times 10^{-3}$)	OS($\times 10^{-3}$)	Ts (s) (2%)	US($\times 10^{-3}$)	OS($\times 10^{-3}$)	Ts (s) (2%)
PID-Thermal [11]		-57.86	12.54	29.98	-52.40	11.93	27.69	-9.20	0.81	38.22
PID-Hybrid [11]		-27.48	12.49	18.23	-34.83	10.45	17.91	-8.90	0.66	34.40
I	PD:(1+PI) PSO	-12.34	4.085	18.87	-11.53	3.715	18.92	-3.03	0.03	24.02
II	PD:(1+PI) PSO	-11.86	1.977	18.64	-10.11	1.59	18.96	-2.77	0.03	23.94
III	PD:(1+PI) PSO	-11.81	0.09	17.95	-8.77	0.07	17.84	-2.71	0.02	22.82
IV	PD:(1+PI) PSO	-8.01	0.08	17.83	-7.91	0.07	17.16	-2.51	0.02	22.68
V	PD:(1+PI) PSO	-12.56	1.41	17.94	-15.88	1.45	17.57	-1.73	0.09	22.87
VI	PD:(1+PI) PSO	-19.34	2.53	18.24	-26.02	2.39	18.21	-1.52	3.33	23.12
VII	PD:(1+PI) PSO	-24.43	2.58	18.59	-26.65	2.41	18.76	-5.72	0.04	23.54
VII I	PD:(1+PI) PSO	-32.09	3.34	18.93	-27.95	2.47	19.08	-10.01	1.49	23.69



(b) (c)

Fig. 8. Response of (a) freq. deviation in area-1 (b) freq. deviation in area-2 and (c) tie line power change for cases.



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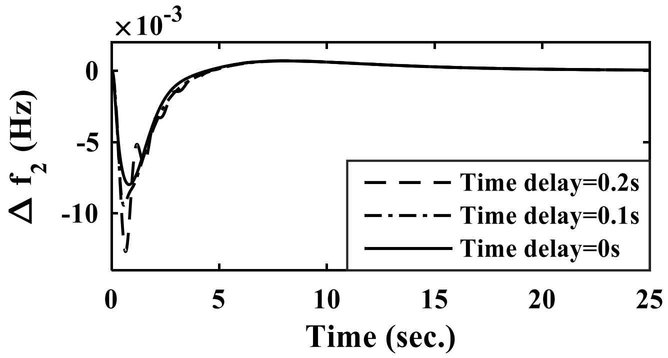

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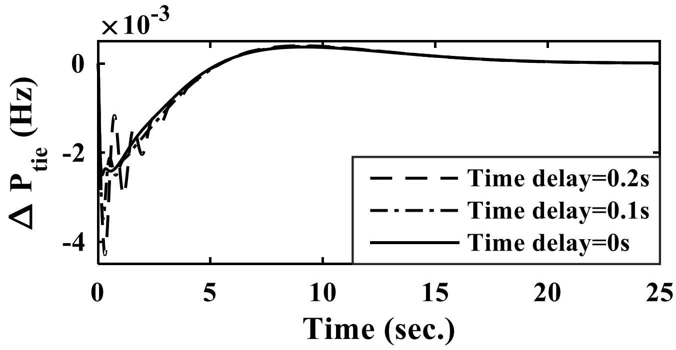
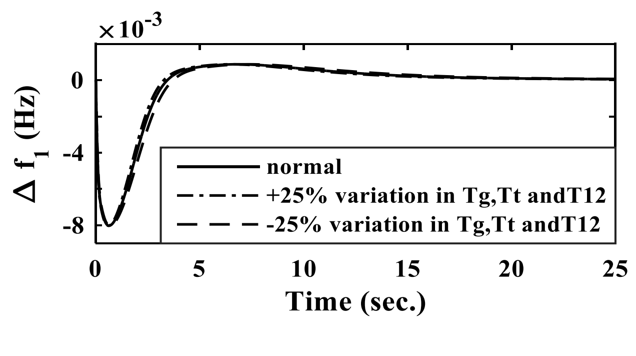
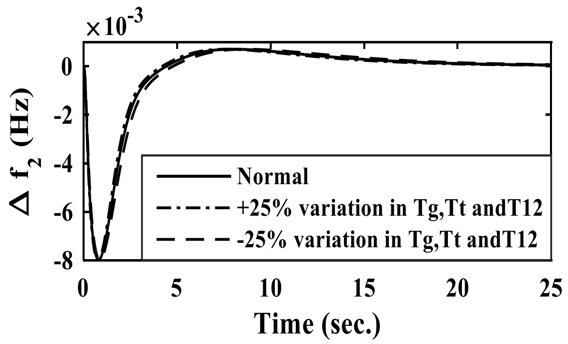


(c)

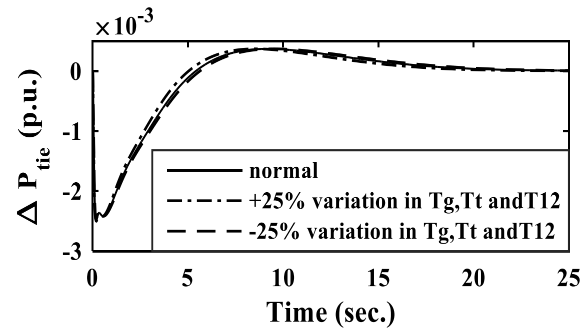
Fig. 9. Response of (a) freq. deviation in area-1 (b) freq. deviation in area-2 and (c) tie line power change for time delays.



(a)



(b)



(c)

Fig. 10. Response of (a) freq. deviation in area-1 (b) freq. deviation in area-2 and (c) tie line power change for system robustness.

To highlight the system efficiency, a time varying load disturbances is applied on the system as displayed in Fig. 11. In the time varying load disturbances, sudden load is applied to the test system at 10 s, 20 s, 40 s, 65 s, 75 s, 115 s, 153 s and 170 s respectively. It is inferred from the Fig.12 that, the suggested controller not only efficiently attenuates the deviation caused by the disturbances but also helps the response to reach the steady state as quick as possible. In addition to that, when renewable sources are connected to the system showed better performance than the conventional hydro thermal plant. This is because the renewable power plant supports the active power at the time of demand- generation imbalances.

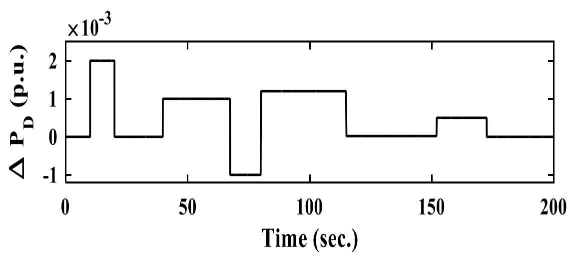
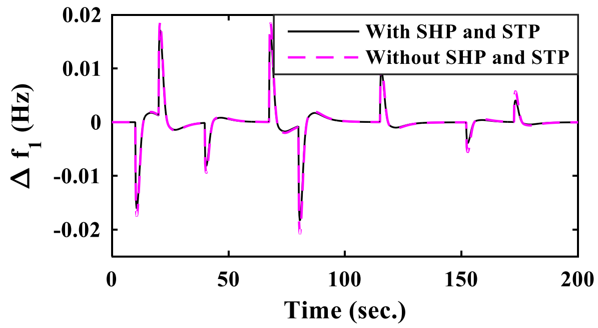
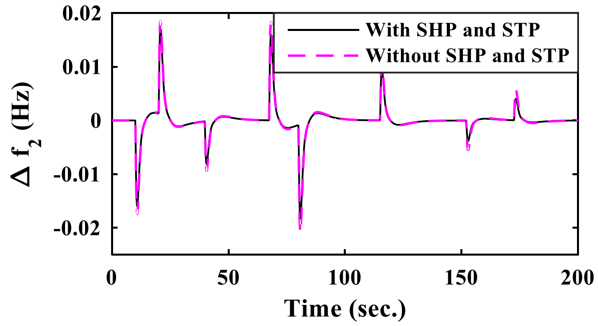


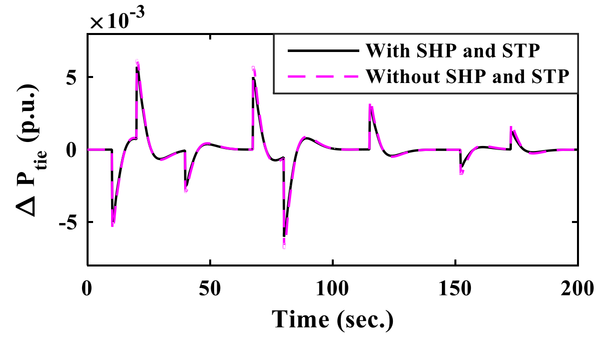
Fig. 11. Dynamic load applied to area -1



(a)



(b)



(c)

Fig. 12. Response of (a) freq. deviation in area-1 (b) freq. deviation in area-2 and (c) tie line power change for dynamic loading.

6. Conclusion

The paper presents the small signal analysis of the 2-area interrelated power structure incorporating renewable energy sources and FACT devices, controlled through multistage controller. The stability analysis of the proposed study is carried out by method of Eigen value analysis and bode plot. It is observed from the simulation that, the numbers of oscillations presents in the response is reduced by using of proposed controller and the same is also verified by the mathematical data in graphically. The effect of time delay, energy storing element and the system dynamics is studied in the test system. By changing the system parameters up to ± 25%, the robustness of the system is studied. The above control method is proved to be effective in transient and steady state subjected to varied step load perturbation and time varying load.

Appendix

R_{eq}=2.4, T_{H1}=0.08 s, T_{T1}=0.3s, K_P=100, Tp=20s, K_I=1, T_1=48.7s, T_W=1s, T_2=0.513, T_R=5, T_{12}=0.0707s, A_{12}=1, B=0.425, T_{2i} = 0.496s, T_{Ri} = 5 s, T_{SHgi} = 36.5s, T_{SHi} = 1s, K_s = 1.8, T_s = 1.8 s, T_{gs} = 1.0 s, T_{ts} = 3.0 s, T_{c1}=0.2587 s; T_{c2}= 0.2481 s, T_{c3}=02333 s; T_{c4}=0.060 s, Ksssc =0.2035, T_{sssc}=0.03 s, T_{smes} = 0.03 s, K_{smes} = 0.297,T_{s1}, T_{s2}, T_{s3}, T_{s4} = 0.121, 0.800, 0.011, and 0.148 s, respectively.

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