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Robustness and Stability Analysis of Renewable Energy Based Two Area Automatic Generation Control

Dillip K. Mishra*‡, Tapas K. Panigrahi**, Asit Mohanty***, Prakash K. Ray***, Arun K. Sahoo*

*Department Electrical Engineering. IIIT, Bhubaneswar, Odisha, India, 751003

** Department Electrical Engineering, PMEC, Berhampur, Odisha, India, 761003

*** Department Electrical Engineering, CET, Bhubaneswar, Odisha, India,751003

(dillipkumarmishra4@gmail.com, tkpanigrahi.ee@pmec.ac.in, asithimansu@gmail.com , pkrayiiit@gmail.com, arunsahoo89@gmail.com)

‡Corresponding Author; Dillip Kumar Mishra, IIIT, Bhubaneswar, Odisha, India, 751003,, Tel: +9437730220, dillipkumarmishra4@gmail.com

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Abstract- Automatic generation control (AGC) plays a vital role in power system operation and control. In this study, an attempt is made to apply a successful evolutionary optimization technique named as firefly algorithm to minimize the Area Control Error (ACE). The firefly algorithm reduces the required control effort for achieving the dynamic response of system like settling time, overshoot and integral square error. The stability aspects of the system are taken care of by applying different criteria and analysis. The execution of firefly algorithm based Proportional Integral Derivative (PID) enhances the performance of the controller in contrast with PID, and Differential Evolution (DE-PID) with reference to stability, overshoot and damping. Further a renewable energy source (RES) such as wind turbine system (WTS) is integrated into the thermal unit in each area to increase the complexity of the system.

Keywords Automatic generation control, Firefly algorithm (FA), Generation rate constraint (GRC), Laboratory Virtual Instrument Engineering Workbench (Lab-VIEW), PID Controller.

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1. Introduction

The frequency regulation of an interconnected power system has been efficiently monitored using Load Frequency Control (LFC) loop. The power exchange between the two area can be done via a link named as Tie-Line[1]. The variation in frequency can be tackled with the suitable implementation of advanced controllers for increasing and decreasing the active power of individual units. There has been wide range of developmental studies in the domain of controllers by many research scholars in the direction of controlling the system frequency for maintaining [2] and improving the stability [3]. For achieving the frequency close to the desired value, during normal and disturbed conditions, it is of prime importance to control the tie-line power exchange among the different regions.

The key objectives of the LFC are for observation of the system frequency and for monitoring the deviations present along the tie-line power exchange across the supervised region.

The imbalance between generation and demand in their frequency range could also be a result of small fluctuation in the load. The kinetic energy extracted from the wind turbine system could be a possible way towards the addressable of the imbalance problem, resulting in the decrease in the frequency. The balance of the system at a single point, for a large power network, when a newly added load has been diverted, is achieved by dropping the power consumption by the load and power associated with the kinetic energy (K.E) separated in distinction to the system. This balance has been attained at the cost of frequency reduction. The maintenance of this balance has been achieved [4] by the system network forming some control action, hence, eliminating the governor action. The decrease in the frequency under such actions has been significant.

Nevertheless, the governor has been put to action with a significant increase in the generator output resulting in larger imbalance. For undoing the imbalance introduced into the system and achieving the balance in the system, the newly added load has been diverted via minimizing the amount of power consumption associated with the existing load and increasing generation by governor action. This result in significant minimization in the amount of K.E that has been extricated in distinction to the system [5], but not wholly and hence, presence of frequency fall has been observed for the aforementioned category of equilibrium with a significant level of reduction from the previous category. Such type of equilibrium has been attained within 10 to 20 seconds following the inclusion of the burden and such kind of action of the governor has been named as primary control [6].

Even following the overview of action of the governor, the considered system has been divergent from its per-defined value; hence, different control approaches are adopted for bringing back the frequency value to its predefined value. The best suited controller for such type of control has been Integral controller and this has been named as secondary control which has been designed to initiate after primary control for bringing the frequency to its predefined value or approximating the same [7]. But the demerit of the controller has been its slow operation. The proposed system is designed with LabVIEW environment which is faster and easy to use [8].

Nomenclature:

AGC: Automatic generation control
LFC: Load frequency control
GRC: Generation rate constraint
DE: Differential evolution
FA: Firefly algorithm
ACE: Area control error
HVDC: High voltage direct current
β: Frequency bias parameter
R: Regulating parameter
T_g: Governor time constant
Tt: Turbine time constant
T_{12}: Synchronizing coefficient
K_r: Reheat gain
T_r: Reheat time constant
P_{12}= Tie line power
ΔP_D:Change in load demand
ΔP_{tie}: Change in tie line power
ΔF: Change in frequency
K_{dc}: HVDC link gain
K_{WTS}: Wind plant gain
T_{WTS}: Wind plant time constant
RES: Renewable Energy Source
WTS: Wind turbine system
KE: Kinetic energy

2. Two Area Power System

2.1. Introduction

The tie-lines are pivotal for the power system interconnections between two or among multiple area-systems, each area providing control and power flow being permitted via tie-lines between the considered areas. Not only frequency of the output of the area of the interconnected unit, but also the tie-line power has also been affected due to the changes in the load demand [9]. To counter this, the disturbances being experienced by the neighboring areas has been monitored by the control system of individual area for establishing the predefined value of frequency of the system and the tie-line power wherein individual region having its own area frequency, tie-line power deviations and area control error. The Area Control Error (ACE) has been defined with the help of the change in frequency ((ΔF_i), tie-line power (ΔP_{Tie}), and frequency bias parameter (β_i)[10]:

$$ACE = B_i \Delta F_i + \Delta P_{Tie} \qquad (1)$$

Therefore, for the restoration of the predefined value of the frequency of the system and the power in the tie-line during disturbance, an appropriated control system has been the necessity in the load frequency control. In practice, the requirement of the load frequency control (LFC) has more been for the interconnected power system than the isolated single area system. The fundamental working principles of an interconnected power system:

- The load demands specific to its own area has to be carried out by the unit itself-during nominal working conditions while addressing the docketed fraction of other member loads as per the proposed agreement.

- The approval for implementation, monitoring, control strategies and equipment in the control area has to be carried out by the system itself proving beneficial for the normal as well as the disturbed conditions [11].

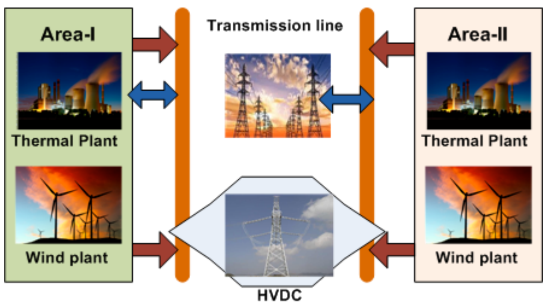


Fig.1: Two area power system.

2.2. *Model of two area power system*

A two-area interconnected power network has been defined as the interconnection existing between the two control areas through tie-line. Fig.1 has demonstrated a two-area power network wherein individual region funds towards its inherent region and the power flows between the regions via tie-line. The proposed model of multi area power system is depicted in Fig.2. Both area-1 & 2 comprises of thermal with reheat power plant. Additionally, GRC and time delay is used for real practice of non-linearity. In this present study, three different controller such as PID, DE-PID and FA-PID controller are employed with respect to their time delays. Each area having 2000 MW generation and 1000 MW loading has been taken place.

The power exchange in interconnected power system can be written as: [12]

$$P_{TieAC} = P_{12\max}\sin(\delta_1 - \delta_2) \quad (2)$$

For minute load change Eq. (2) can be formulated as:

$$P_{TieAC} = T_{12\max}(\Delta\delta_1 - \Delta\delta_2) \quad (3)$$

In this case T_{12} is synchronizing coefficient can be formulated as :

$$T_{12} = P_{12\max}\cos(\delta_1 - \delta_2) \quad (4)$$

2.3. Modelling of HVDC for LFC

In this study we have also considered parallel HVDC link for dynamic stability enhancement. Although each HVDC link are tailor made to encounter specific requirement of its use. A transfer function model is representing the parallel HVDC link. The operation of HVDC link is operated in the region of constant current control mode. The minute change in AC tie line power ΔP_{TieAC} can be written as:-

$$P_{TieAC} = \frac{2\pi T_{12}}{s}(\Delta F_1 - \Delta F_2) \quad (5)$$

The minute change in AC tie line power ΔP_{TieAC} can be written as

$$P_{TieDC} = \frac{K_{dc}}{1 + sT_{dc}}(\Delta F_1 - \Delta F_2) \quad (6)$$

The total tie line power exchange, Ptie12 can be written as:

$$P_{Tie12} = P_{TieAC} + P_{TieDC} \quad (7)$$

The change in tie line power can be formulated as:

$$\Delta P_{Tie12} = \Delta P_{TieAC} + \Delta P_{TieDC} \quad (8)$$

The ACE_1 and ACE_2 with AC-DC link can be defined as:

$$ACE_1 = \beta_1\Delta F_1 + \Delta P_{TieAC} + \Delta P_{TieDC} \quad (9)$$

$$ACE_2 = \beta_2\Delta F_2 + \alpha_{12}(\Delta P_{TieAC} + \Delta P_{TieDC}) \quad (10)$$

In this case β_1 and β_2 are frequency biased parameters and, the area size ratio α_{12} is given by:

$$\alpha_{12} = P_{r1} / P_{r2} = -1 \quad (11)$$

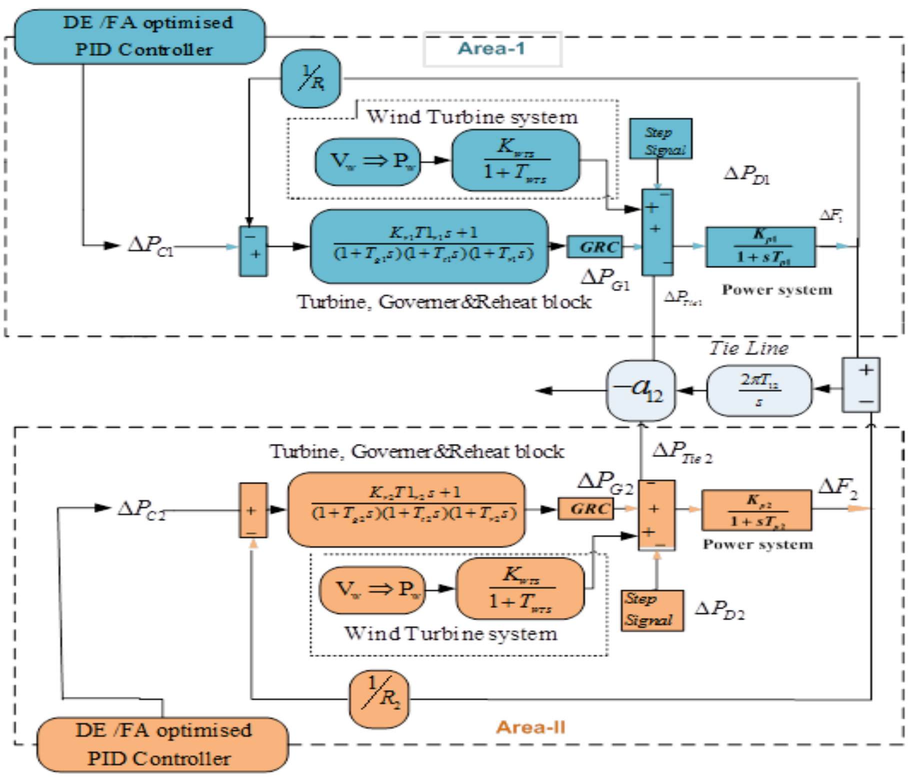


Fig.2. Mathematical modelling of two area power system.

2.4. Wind Turbine System

Nowadays wind power generation is also a vital source of renewable energy. The output power of the wind generator (WTG) subject to on wind speed V_W. The total wind speed can be estimated as the sum of base wind, gust wind, ramp wind and noise wind speed. The equation of total wind speed is as follows [13] [14] [15].

$$V_{WB} = K_B \quad (12)$$

Where K_B is a constant

There are different wind speed component which has been described as follows.

The gust wind speed can be expresses as

$$V_{WG} = \begin{cases} 0, & t < T_{1G} \\ V_{COS}, & T_{1G} < t < T_{1G} + T_G \\ 0, & T_{1G} + T_G < t \end{cases} \tag{13}$$

In this case

$$V_{COS} = (MAXG/2)\left\{1\text{-}2\cos\pi\left[t/T_G - (T_{1G}/T_G\,])\right\}\right. \tag{14}$$

T_G, T_{1G}, & MAXG, are the gust period, gust starting time & gust peak respectively [16].

The ramp wind speed can be expresses as

$$V_{WR} = \begin{cases} 0, & t < T_{1R} \\ V_{ramp}, & T_{1R} < t < T_{2R} \\ 0, & T_{2R} < t \end{cases} \tag{15}$$

In this case

$$V_{ramp} = (MAXR)\left\{1 - (t - T_{2R})/(T_{1R} - T_{2R})\right\} \tag{16}$$

T_{1R}, T_{2R}, MAXR are the ramp, ramp start time, ramp maximum time respectively. The ranges of MAXR are -3 to 7.5.

3. Controller

PID controller is one of the most widespread feedback controllers that is used in the industry now a days.

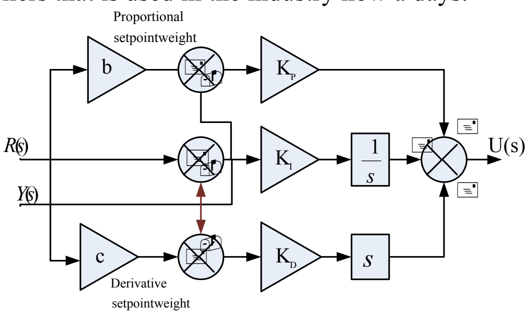


Fig 3. PID controller structure.

It can also offer admirable control performance in spite of the diverse dynamic characteristics of process plant [17]. The transfer function of PID controller is given by equation (17) and is shown in Fig.3

$$G_C = K_P + \frac{K_I}{S} + K_D S \tag{17}$$

4. Optimization Technique

4.1. Firefly Algorithm

This particular paper discusses the implementation of firefly algorithm for optimization of different parameters of the proposed system. This algorithm has been proposed by Yang which is based on flashing of the light shown by the biochemical process. The flashing light represents the primary signal for the purpose of mating and it is totally dependent on gathering different attributes of the fireflies [18]. The detail process has been described below.

- The fireflies are represented as either unisex and they pay little attention to their sex.
- The engagement of fireflies is according to their brilliance. The engaging capability is proportional to the intensity if light. Further for two glimmering fireflies the less splendid fireflies' moves towards the brighter fireflies. As because splendor corresponds to separation, the phenomenon of more signing indicates less separation in between two fireflies. Also if two blazing have same time of brilliance, they move in an arbitrary manner. The detection of the brilliance of fireflies has been represented by an objective function that has been influence by the brilliance.

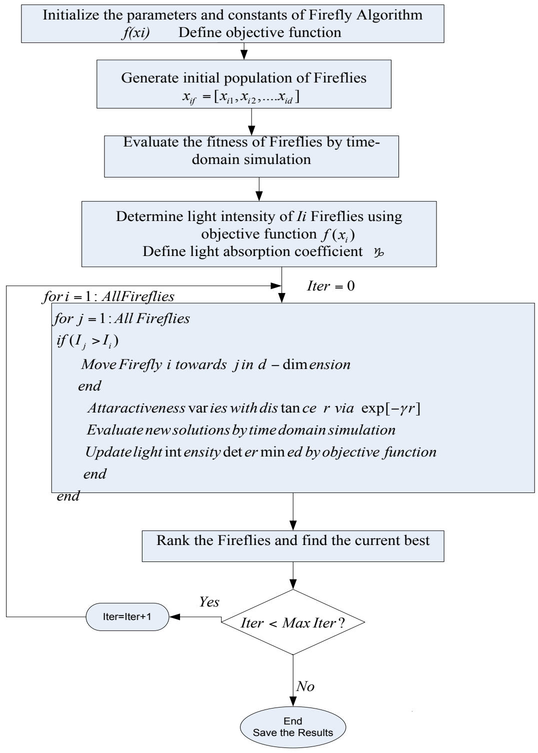


Fig.4. Firefly Algorithm flowchart.

In order to have maximization of the performance of the firefly algorithm couple of main problems should be addressed regarding the type of light intensity (I_0) & attractiveness (V_0). The overall controlling of the attractiveness of the firefly has been done by the light intensities and totally depends of the objective functions. The light intensity becomes different from the separation in a monotonous & exponential manner.

$$I(r) = I_0 e^{-\gamma r} \tag{18}$$

Where I_0 represents the actual light intensity & has been denoted by the light absorption co-efficient value. The actual attractiveness of the firefly is governed by the intensity of light observed from the by nearby fireflies. Further it depends upon the intensity of light visualizing by the by the nearby fireflies. The mathematical expression of the attractions of the firefly is given as

$$\beta=\beta_0 e^{-\gamma r^2} \tag{19}$$

In this case β_0 represents the attractiveness during $r = 0$.

The partition lies in among the fireflies has been communicated as Euclidean separation. Which is expresses as

$$r_{ij}=\left\| s_i - s_j \right\| = \sqrt{\sum_{k=1}^{k=n} (s_{ik} - s_{jk})^2} \tag{20}$$

In this case 'n' represents the dimension of problem.

The actual development of ith firefly has been attracted to a different attractive firefly. The overall development of the fireflies is made of 3 tones such as the current place of ith firefly, appeal towards more appealing firefly, and then a random which is made of randomization constraint α & irregular number ε_i in a range of [0-1].

The development is communicated as:

$$s_i = s_i + \beta_0 e^{-\gamma r_{ij}^2}(s_i - s_j) + \alpha\varepsilon_i \tag{21}$$

The controlling activity of firefly can be initiated with three main parameters such as i) randomization parameter, ii) attractiveness, iiii) absorption co-efficient

Generally the parameters are suggested in a range of [0-1].The quantities of the firefly are to be chosen up based on the satisfying execution with not as much of computational actions. Different steps have been initiated for choosing the control parameters. The final value of the tuned parameters area, the exact figure of fireflies = 5; iteration = 50; $\beta = 0.2$; $\alpha = 0.5$ and $\gamma = 0.5$.

4.2. Objective function

The fundamental aim of the LFC is to lessen the ACE with a very less span of time. To minimize the area control error value, the cost function is mentioned as

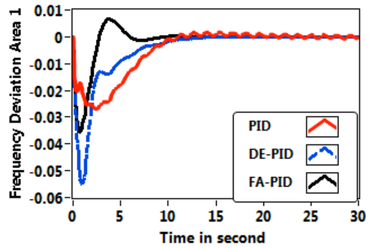
$$f=\int_0^t \left|\Delta w_1 - \Delta w_2\right|.tdt \tag{22}$$

In this case dt is change in time ΔW_1 & ΔW_2 are the deviation of frequency in area-I & area-2 correspondingly. Present study, a minute change in load of 1% is in area-1

5. Simulation Results

5.1. (AC Links only)

In this study, two equal area power system is considered. In both area-1 and area-2 thermal units with wind turbine system has been employed. Here, both 10 % step loading and random loading has been applied and simulated. Three types of controllers are used to analyses the system characteristics such as PID, DE-PID and FA-PID. It is evident that FA tuned PID controller offers more steady response than others. The performance characteristics of the proposed system are depicted in Fig.5 and performance index is presented in Table.3.



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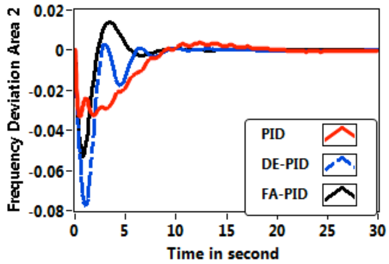

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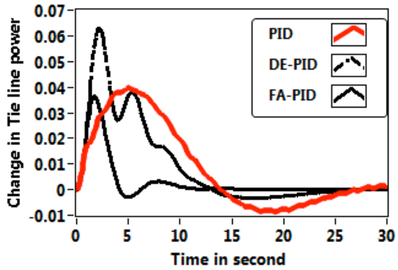

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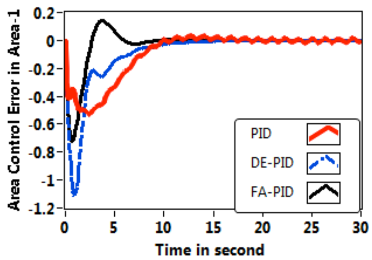

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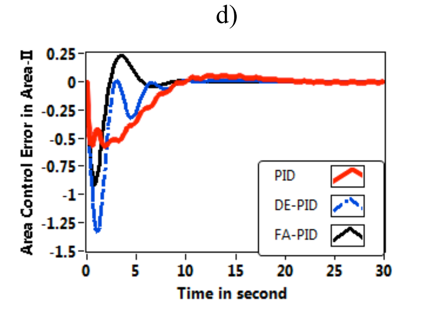

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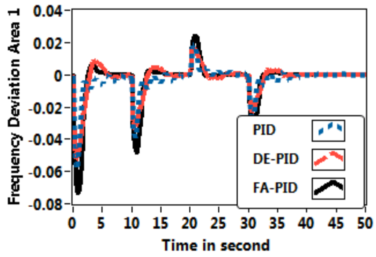

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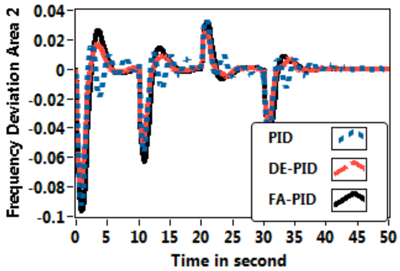

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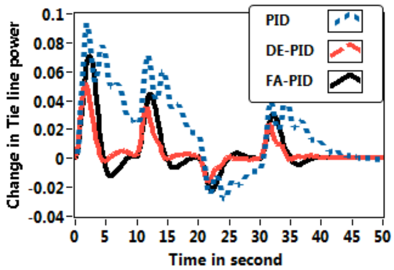
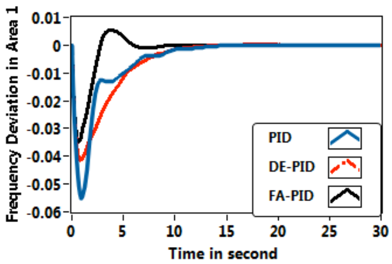


h)

Fig. 5.(a-e , 10 % Step load change in area-1 and area-2) & (f-h, random loading) a) ΔF1 , b) ΔF2 , c) ΔPtie d)ACE-I e) ACE-II, f) ΔF1 , g) ΔF2, h) ΔPtie

5.2. AC-DC Link

In this study, two area power system with AC-DC link is considered. Three types of controllers are used to analyse the system characteristics such as PID, DE-PID and FA-PID. It is evident that FA tuned PID controller with HVDC link provides more steady results than AC links only. The performance characteristics of the proposed system are portrayed in Fig.6 and performance index is presented in Table.2.



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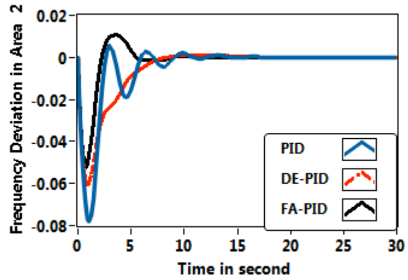

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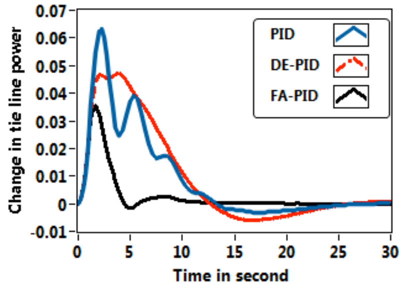

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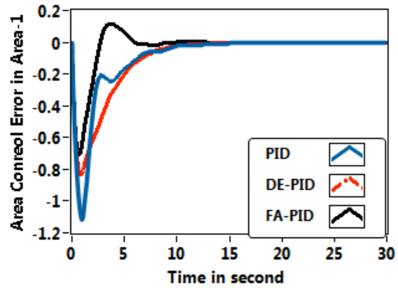

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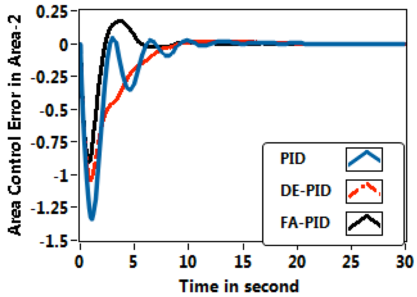

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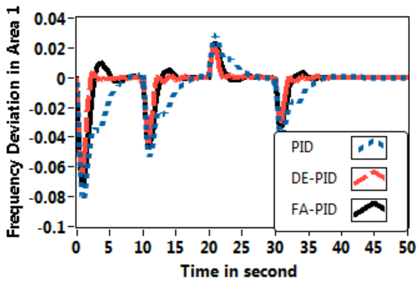

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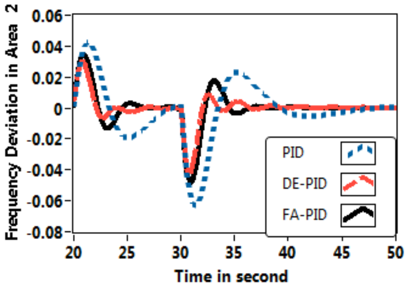

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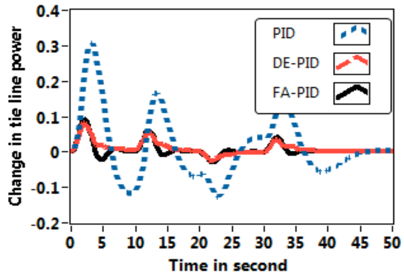
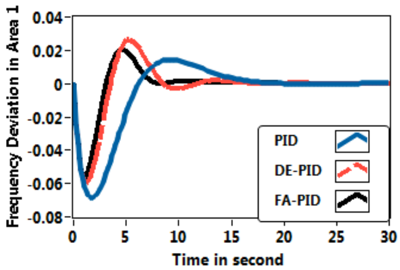


h)

Fig. 6.(a-e , 10 % Step load change in area-1 and area-2) & (f-h, Random loading) a) ΔF1 , b) ΔF2 , c) ΔPtie d)ACE-I e) ACE-II, f) ΔF1 , g) ΔF2, h) ΔPtie

5.3. AC-DC Link with Reheat turbine

Furthermore, reheat turbine with AC-DC link in two area power system is considered. In both area-1 and area-2 thermal units and WTS has been taken. Three types of controllers are used to analyses the system characteristics such as PID, DE-PID and FA-PID. It is noticed that FA optimized PID controller with reheat gives more stable results than above studies. The performance characteristics of the proposed system are shown in Fig.7 and performance index is shown in Table.3.



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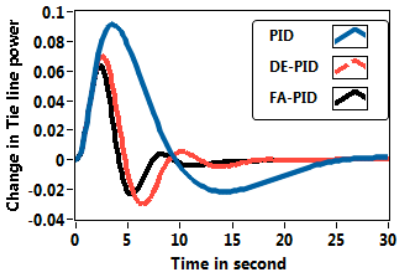

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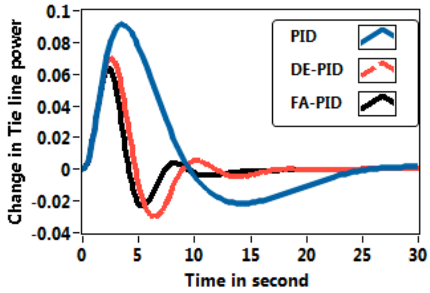

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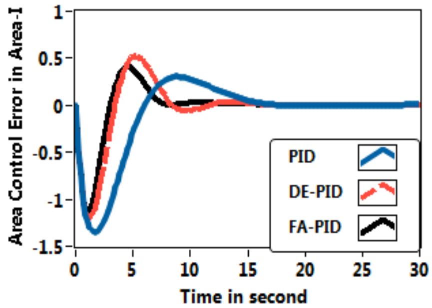

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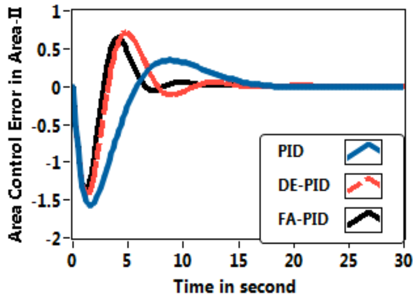

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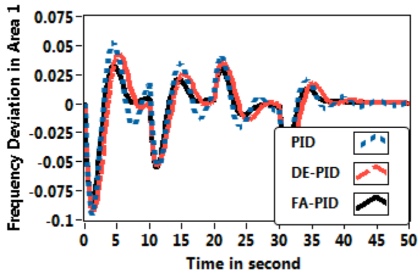

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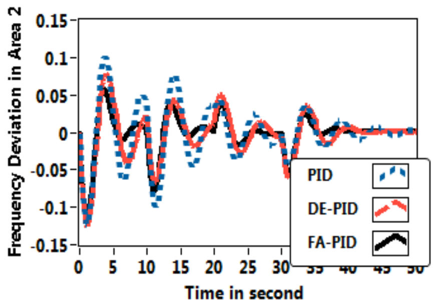

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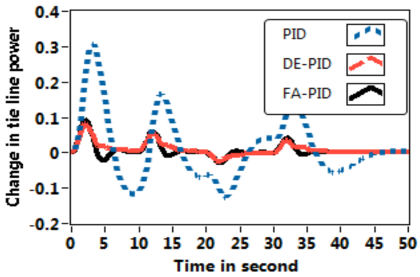


h)

Fig. 7.(a-e , 10 % Step load change in area-1 and area-2) & (f-h, Random loading) a) ΔF1 , b) ΔF2 , c) ΔPtie d)ACE-I e) ACE-II, f) ΔF1 , g) ΔF2, h) ΔPtie

Table-1. Performance index

Controller	ΔF_1		ΔF_2		ΔP_{Tie}		ACE_1		ACE_2	
	Ts	Overshoot	Ts	Overshoot	Ts	Overshoot	Ts	Overshoot	Ts	Overshoot
PID	24.18	0.001	25.05	0.024	28.08	0.079	23.32	0.005	25.08	0.009
DE-PID	16.24	0.001	17.37	0.003	25.28	0.061	16.19	0.004	16.94	0.008
FA-PID	10.94	0.004	12.17	0.012	16.81	0.031	09.84	0.002	12.05	0.004

Table. 2 : Performance index

Controller	ΔF_1		ΔF_2		ΔP_{Tie}		ACE_1		ACE_2	
	Ts	Overshoot	Ts	Overshoot	Ts		Ts	Overshoot	Ts	Overshoot
PID	19.73	0.001	20	0.024	27.94	0.079	18.81	0.003	19.82	0.004
DE-PID	18.38	0.001	19	0.003	24.08	0.061	17.82	0.002	18.34	0.002
FA-PID	9.56	0.004	13	0.012	15.97	0.031	9.01	0.002	9.03	0.001

Table.3. Performance index

Controller	ΔF_1		ΔF_2		ΔP_{Tie}		ACE_1		ACE_2	
	Ts	Overshoot	Ts	Overshoot	Ts	Overshoot	Ts	Overshoot	Ts	Overshoot
PID	17.35	0.001	18.59	0.024	25	0.079	16.28	0.003	18.01	0.003
DE-PID	16.29	0.001	17.94	0.003	17	0.061	15.71	0.004	17.34	0.004
FA-PID	7.18	0.004	11.57	0.012	12	0.031	7.04	0.001	11.08	0.002

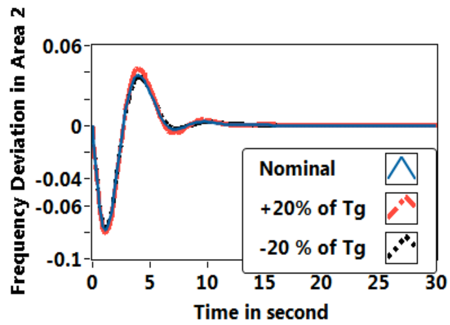
Table-4. Performance index with different paramaeter variation

Loading	Parameter	T_g	β	*R*	T_{12}
No Loading	ΔF_1	7.18	7.17	7.17	7.21
	ΔF_2	11.57	11.28	11.57	11.57
	ΔP_{Tie}	12.04	12.31	12.04	12.04
+20% Loading	ΔF_1	07.25	07.18	07.27	07.24
	ΔF_2	11.83	11.49	11.84	11.84
	ΔP_{Tie}	12.36	12.07	12.34	12.37

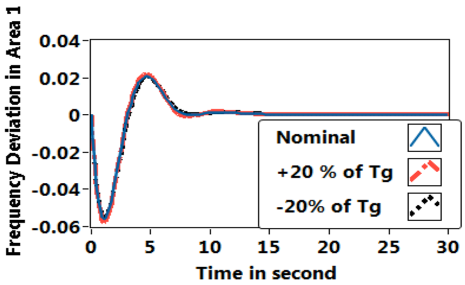
-20% Loading	ΔF_1	07.16	07.19	07.14	07.17
	ΔF_2	11.56	11.30	11.55	11.57
	ΔP_{Tie}	12.04	12.06	12.02	12.03

5.4. Sensitivity analysis

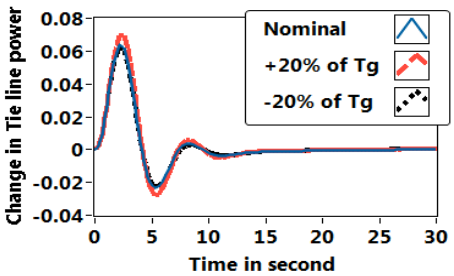
In order to verify the robustness of the system, sensitivity analysis has been measured. In this study ±20 % perturbation in parameter setting has been taken. The parameters are loading, turbine time constant (T_t), governor time constant (T_g), synchronizing coefficient (T_{12}), regulating parameter (R). From the Fig.9, it is noticed that the proposed system is robust because there is no change in system performance with ±20 % loading. Also random loading is measured. The analysis is presented in Table 4



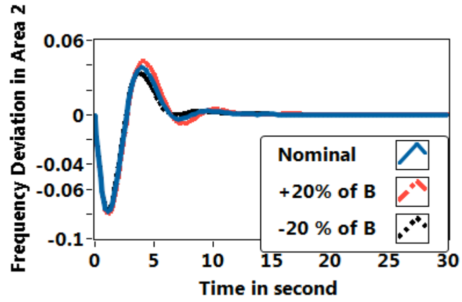
a)



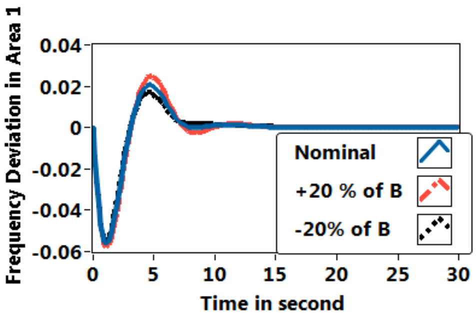
b)



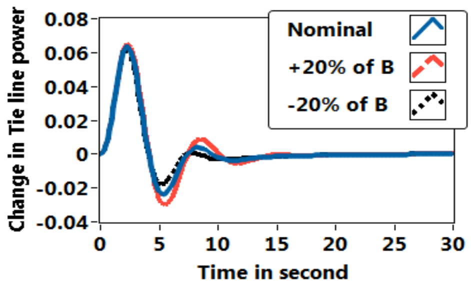
c)



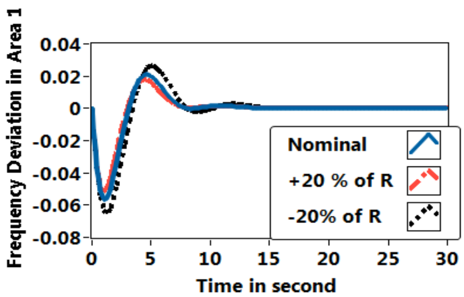
d)



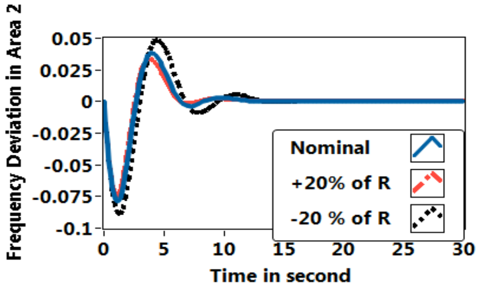
e)



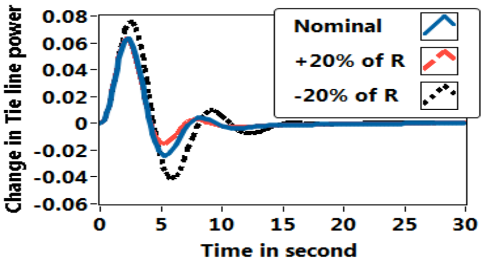
f)



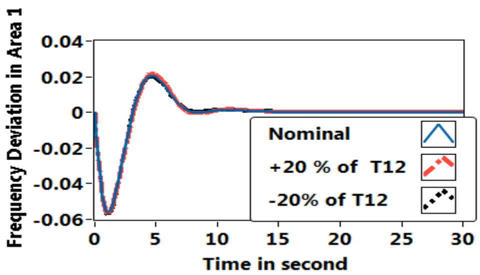
g)



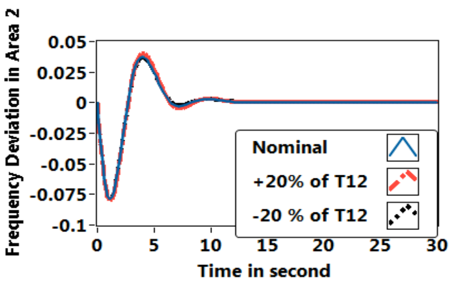
h)



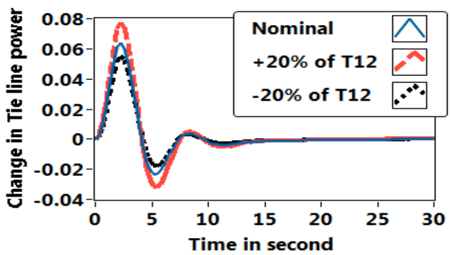
i)



j)



k)



l)

Fig. 8.(a-l) Sensitivity analysis characterstics with ±20 % loading

5.5. Stability Analysis

Further study in stability analysis of the system has been done with and without controllers and a comparative performance analysis has been done based on Bode, Nyquist circle criterion, nicholas chart, root locus as shown in Fig.9.

UnCompensatedsystem **Compensated system**

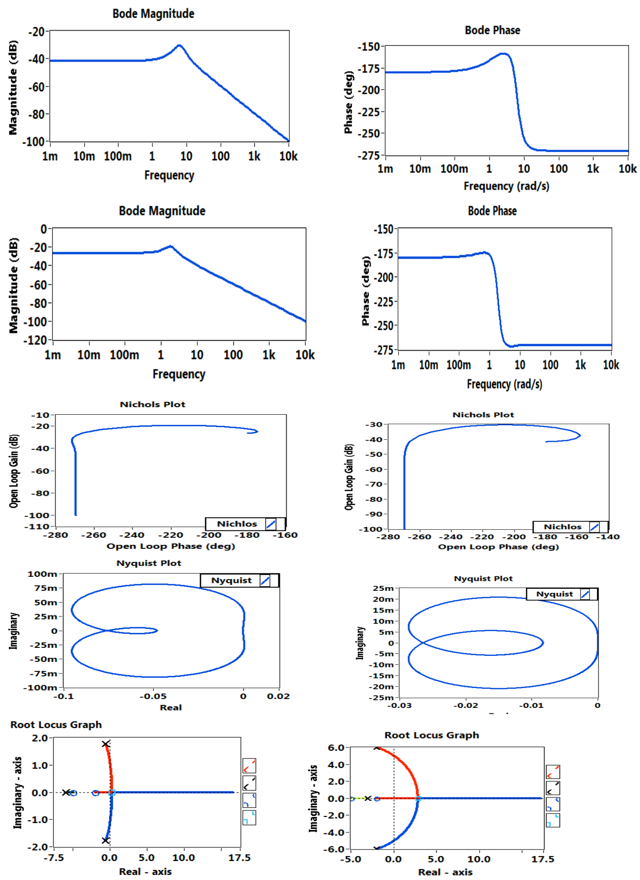


Fig.9. Stability analysis

6. Conclusion

This article addresses a detail stability analysis of a two area interconnected multi source power system, integrated with renewable energy source (wind turbine system) in each area. In order to conduct the stability analysis of proposed hybrid model, reduction of generation of thermal power plant is compensated by wind power plant for fuel saving and minimization of emission. The optimum gains of the controller are achieved by the implementation of firefly algorithm and it is compared with the gains found by the DE-based algorithm. Further, results have been found out by adding AC-DC link, reheat. Subsequently, random loading and sensitivity analysis are done with ±20% parameter variation. Finally, stability analysis is done using frequency response and time response analysis such as bode plot, nyquist plot, root locus.

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