Application of Modern Heuristic Algorithm to Automatic Generation Control of Hybrid Electric Power System with GRC

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Abstract— **This paper describes the application of modern heuristic optimization algorithm, called pattern search algorithm, to automatic generation control of hybrid interconnected electric system. In this paper, the pattern search algorithm has been proposed for tuning of controller. The controller parameters related to each area have been tuned by the proposed algorithm. Ant colony optimization and a refined Ziegler-Nichols tuning technique have been used as benchmarks. The superiority of the proposed load frequency controller has been demonstrated by comparing with the benchmarks. The inclusion of generation rate constraint results in challenging task for the realization of an effective controller design. This difficulty is further enhanced with step load and random load variations.**

The effectiveness and validity of the proposed controller are investigated for hybrid distributed generation electric system with generation rate constraint and tie-line operation. The results demonstrate that the adopted optimization technique has presented superior convergence robustness when compared with the benchmarks without/with energy storing element (BESS) for step load and random load variations.

Keyword-Automatic Generation Control, Modern Heuristic Algorithm, Generation Rate Constraint, Step load disturbances.

I. INTRODUCTION

From the last few decades with increase in population and industries, the demand for generation of electrical energy continuously increases. But because of gradual decrement in fossil fuels and more in fuel cost, the required power demand may not be fulfilled by the conventional power generations. To overcome this difficulty, renewable power generation sources like offshore wind, bio-fuels, photovoltaic etc are gaining the popularities due to their advantages such as less capital investment, low environmental pollution and low transmission losses. Wind energy is an emerging as leading and competitive renewable energy source. In this context, renewable source (like offshore wind turbine) and non renewable source (like Thermal power system) are integrated with stand-by diesel engine generator (DEG) as well as energy storing element such as Battery storage system (BESS) to construct hybrid power system for effective control of supply and demand power balance. The power supplied by the proposed hybrid power system can be effectively delivered to the connected loads with appropriate control and coordination among various sub-systems. Battery energy storage system (BESS) is economical and stores effectively to release energy during the peak load demand. Diesel engine generator (DEG) may be introduced into the hybrid system as standby source to meet the power demand so that better control can be achieved. The offshore wind farms can transmit bulk power over long distances. Because of intermittent characteristics of offshore wind turbine generators, there is mismatch between total power generation, load demands and leads to deviation in system frequency. If this frequency deviation is not controlled, it may create instability in the system performance [1], [2].

How much area of interconnected power system should response to system frequency variation can be decided by the tie line bias. Under normal operating condition each control area takes care of its frequency variations, when any disturbances/abnormal conditions occurs the tie line manage the power flow such a way that the frequencies of the control areas remain in the specified limit. The work presented in this paper is organised as follows. The Section-II describes modelling of various energy sources, storage elements and proposed interconnected hybrid power system in the form of transfer functions. This is followed by descriptions on tuning of controller in Section-III. The simulation results and discussions of interconnected hybrid system are in Section-IV. Finally conclusions are given in Section-V.

II. PROPOSED HYBRID ELECTRIC POWER SYSTEM WITH GRC

Since the AGC study being limited to small variations, the system models are usually represented by linealized models in order to minimize the complexities in modeling and frequency deviation analysis. As a result in simulation part, the system nonlinearities have not been considered and systems are simulated in simplified form as linear first order transfer functions.

A. Energy Storing System

Because of advancement in power electronic technology, Energy storing system (Battery Energy Storing Systems (BESS)) are using recently. The BESS consists of DC battery bank connected to AC system through power converter and transformer. With the proper control strategy, the BESS can provide good change of active and reactive in both positive and negative values [4, 5]. The Transfer function of battery energy storage system is represented by approximated first order lag as

$$G_{BESS}(s) = \frac{K_{BESS}}{1 + sT_{BESS}} = \frac{\Delta P_{BESS}}{\Delta f}$$

Where K_{BESS} = Gain constant of BESS and T_{BESS} = Time constant of BESS.

B. Wind Power Generation

The power generated by the wind turbine generator depends on wind velocity[6, 7]. The wind velocity is algebraic sum of base wind velocity V_{wb}, gust wind velocity V_{wg}, Ramp wind velocity V_{wr} and noise wind velocity V_{wn} i.e

$$V_w = V_{wb} + V_{wg} + V_{wr} + V_{wn}.$$

The mechanical output power of wind turbine generator is $P_w = ½ \rho A_r C_p V_w^3$. Where ρ = Air density in kg/m^3, A_r = Swept area of blade in m^2, C_p = power coefficient which is function of blade pitch angle (β) and tip speed ratio (λ). The transfer function of Wind Turbine Generator (WTG) is given by linear first order lag as

$$G_{WTGk}(s) = \frac{K_{WTG}}{1 + sT_{WTG}} = \frac{\Delta P_{WTGk}}{\Delta f}$$

Where k = 1, 2 and K_{WTG} = Gain constant of WTG and T_{WTG} = Time constant of WTG.

C. Interconnected Thermal System

The main difference between AGC of multi-area system and that of single area system is, the frequency of each area of multi-area system should return to its nominal value and also the net interchange through the tie-line should return to the scheduled values. So a composite measure, called area control error (ACE), is used as the feedback variable. If the load increases, the speed of the alternator reduces slightly. The governor of any thermal unit reacts to this speed variation and permits the entry of some more steam from the boiler to turbine which increases the speed. Many forms of the governor system have been devised all of which includes, the variation of the turbine-alternator shaft speed as the basis on which the change of position of the turbine. Typical speed droop characteristics for most governor range between 5 to 10%. The transfer function of speed governor with drooping characteristics is (T_{sg} = time constant of speed governor)

$$Gsg(s) = \frac{1}{1 + sTsg}$$

Turbine dynamics are very important because they also affect the overall response of the generating plant to load changes. *Non-reheat turbines* are first-order units. After passing the control valve the high pressure steam enters the turbine via the steam-chest that introduces time delay T_{nrt} usually in order of 0.2 - 0.5s [8]. The *Reheat turbines* are modelled as second-order units because of presence of high and low steam pressure. It is more efficient and is used for modern-day large sets. The transfer functions of non-reheat and reheat turbines, respectively, are (T_t = time constant of Non-reheat turbine, T_{tr} = time constant of reheat turbine)

$$Gnr(s) = \frac{1}{1 + sTt}; \qquad Gsg(s) = \frac{1 + sCTtr}{(1 + sCTt)(1 + sTlpr)}$$

The Generator which is supplying local load and is not supplying power to another area via a tie-line. Suppose there is a real load change of ΔP_D. Due to the action of the turbine controllers, the generator increases its output by the amount ΔP_G. The net surplus power $\Delta P_G - \Delta P_D$ will be absorbed by the system of generator with load damping (D) effect. The transfer function of generator with load damping or power system is (K_{ps} = Gain constant of power system, T_{ps} = Time constant of power system)

$$Gps(s) = \frac{1}{D + sM} = \frac{Kps}{1 + sTps}$$

Practically, all power systems now a days are interconnected by number of tie-lines with the neighbouring areas. When the frequency variations in two areas are different, a power exchange occurs through the tie-line between the connected two areas. The Laplace transform of tie line is

$$\Delta P_{tie\,ij}(s) = \frac{T_{ij}(\Delta F_i(s) - \Delta F_j(s))}{s}$$

Where ΔP_{tieij} is tie line power exchange between areas i and j, and T_{ij} is the tie-line synchronizing coefficient between area i and j.

The nominal values of Turbines, Power system, Diesel Energy Generation (DEG), Battery Energy Storing System (BESS) are listed in appendix (see Table III) [5, 8].

D. Configuration of Hybrid Electric System

The conventional interconnected power system is modified with Reheat thermal turbine and DEG in Area-I, Non-reheat thermal turbine with Generation Rate Constraint (GRC) in Area-II and Reheat thermal turbine and BESS in Area-III. The Block diagram of interconnected hybrid electric system is shown in Fig. 1. Each area has Rated capacity 1500MW with nominal load capacity of 1000MW, maximum tie-line power is 200MW and synchronizing co-efficient is 0.545. The nominal values of Speed governor, Turbine and Power system are shown in Table-I [7, 8]. The nominal parameters of Area-I & III were collected from Sothern Grid and Neively Lignite Corporation, Tamil Nadu, India. Area-II data is from RTPP, A.P. India. Rated capacity P_r = 2000 MW, P_{tiemax} = 200 MW, $(\delta_1 - \delta_2) = 30^0$, Nominal Frequency f^0 = 50 Hz, $D_i = 8.33x10^{-3}$, Syn. Coefficient T_{ij} = 0.545.

TABLE I. Nominal parameters of Speed Governor, Turbine and Power System of all areas.

Parameters	AREA-I	AREA-II	AREA-III
Speed Governor Time constant	0.08	0.08	0.08
Speed Governor Regulation	2.4	2.0	2.4
Power System Gain Constant	20	15	20
Turbine Time Constant	0.3	0.3	0.3
Coefficient of re-heat steam turbine (HP)	0.3	-	0.5
Reheat Time Constant (LP)	10	-	10

A well designed power system should be able to provide the acceptable levels of power quality by keeping the frequency and voltage magnitude within tolerable limits. Changes in the power system load affects mainly the system frequency, while the reactive power is less sensitive to changes in frequency and is mainly dependent on the fluctuations of voltage magnitude. Maintaining power system frequency at constant value is very important for health of the power generating equipment and utilization equipment at customer end ([14-16]).

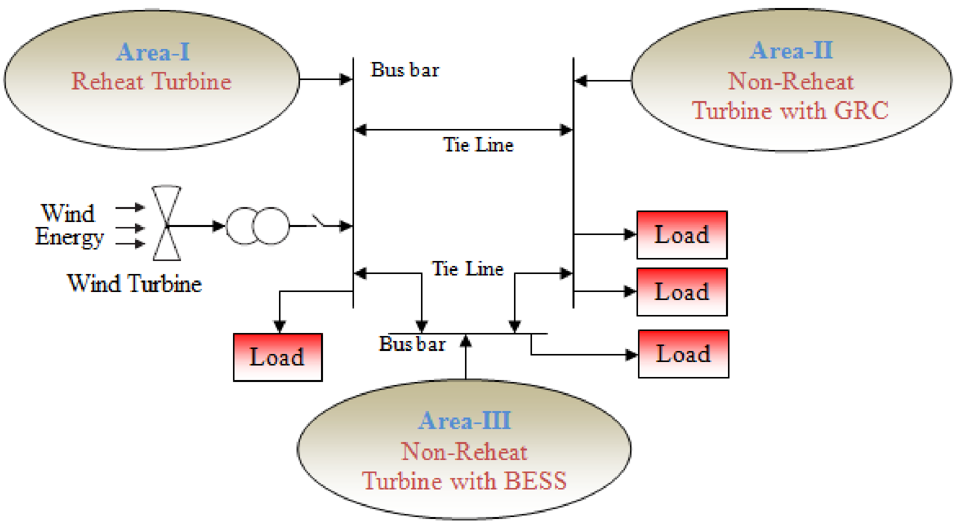


Fig. 1. Configuration of Hybrid Electric Power System with Step Load variations

III. TUNING OF CONTROLLER

The job of automatic frequency regulation is achieved by governing systems of individual turbine-generator, Automatic Generation Control (AGC) or Load frequency control (LFC) system of the power system. The AGC or LFC system solely cannot control the disturbances, it need another controller that makes the steady state error to zero. The tuning of the PID load frequency controller of power system that it has to bring frequency of each area to its nominal value and also the change in tie-line power should return to the scheduled values. In this paper different types of controllers like conventional and heuristic controller are designed for inter-area electric power system with different turbine units in different areas. With the proposed controller, the system dynamic performance was observed and compared with conventional controller.

A. Refined Z-N Tuning

The main drawback of conventional Z-N tuning [9] is it exhibits large overshoot and more oscillations in set-point response, to overcome this, a refinement to such a PID controller tuning algorithm can be obtained with the help of set-point weights [10]:

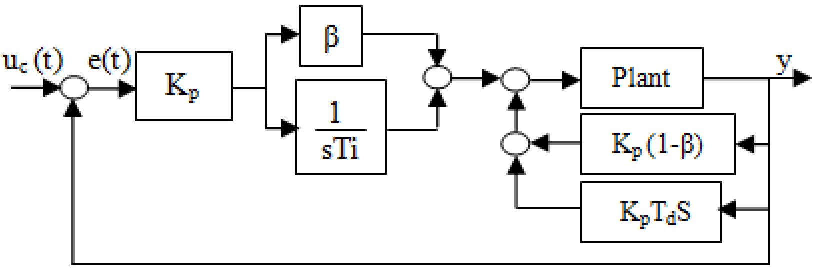


Fig. 2. Refined PID controller structure

The block diagram of refined PID control structure is as shown in Fig. 2. Comparing with the typical feedback control structure, the controller $G_c(s)$ and the feedback H(s) can be written as

$$G_c(s) = K_p\left[\beta + \frac{1}{sT_i}\right] \quad \text{and} \quad H(s) = \left[\frac{T_iT_d\beta(N+2-\beta)S^2/N + (T_i+T_d/N)S + 1}{(T_i\beta S+1)(T_dS/N+1)}\right]$$

Define the normalized delay constant τ as $\tau = L/T$ and constant k as $k = K_c k$. For different limits of the terms τ and k, the PID controller gains are suggested as follows:

- If $2.25 < k < 15$ or $0.16 < \tau < 0.57$, use the original Z-N design gains. To keep the overshoot less than 10% or 20%, β should be evaluated as

$$\beta = \frac{15 - k}{15 + k} \quad \text{or} \quad \beta = \frac{36}{27 + 5k}$$

- If $1.5 < k < 2.25$ or $0.57 < \tau < 0.96$, the integral parameter T_i in Z-N controller should be changed to $T_i = \mu\, T_d$, where

$$\mu = 0.444k \quad \text{and} \quad \beta = 0.471(\mu - 1)$$

- If $1.2 < k < 1.5$, to keep the overshoot < 10% , the parameters of the PID should be refined as

$$K_p = \frac{5}{6}\frac{(12 + k)}{(15 + 14k)}, \quad T_i = 0.2 + \frac{4}{75k}$$

B. Ant Colony Optimization

Nowadays most of the researchers focused on new algorithms, called Metaheuristic, to eliminate the difficulties and drawbacks in classical and conventional tuning methods. The use of Metaheuristic has significantly increased the ability of finding very high quality solutions to hard and practically relevant combinatorial optimization problems in a reasonable time. Differential Evaluation algorithm (DE), Grey Wolf Optimizer algorithm (GOW), Cuckoo Search (CS), Multi Objective Optimization (MOO), Pattern Search (PS), Teaching Learning Based Optimization (TLBO), PSO and so on are comes under Metaheuristic algorithms [11]. The contribution of current work is the use of the optimization methods, namely Ant Colony and Pattern Search techniques for optimal tuning of PID controller.

The *pseudo-code* for Ant Colony Algorithm is as shown below:

Procedure ACO Metaheuristic
Set parameters, initialize pheromone trails
while (termination condition not met) **do**
Construct Ants Solutions
Update Pheromones
end
end

In this paper, Ants number (NA) is 100, evaporation rate (ρ) is 0.95, Number of Iterations (ITR) are 100 and Number of parameters are 3. The flowchart of Ant Colony Optimization is shown in Fig. 3.

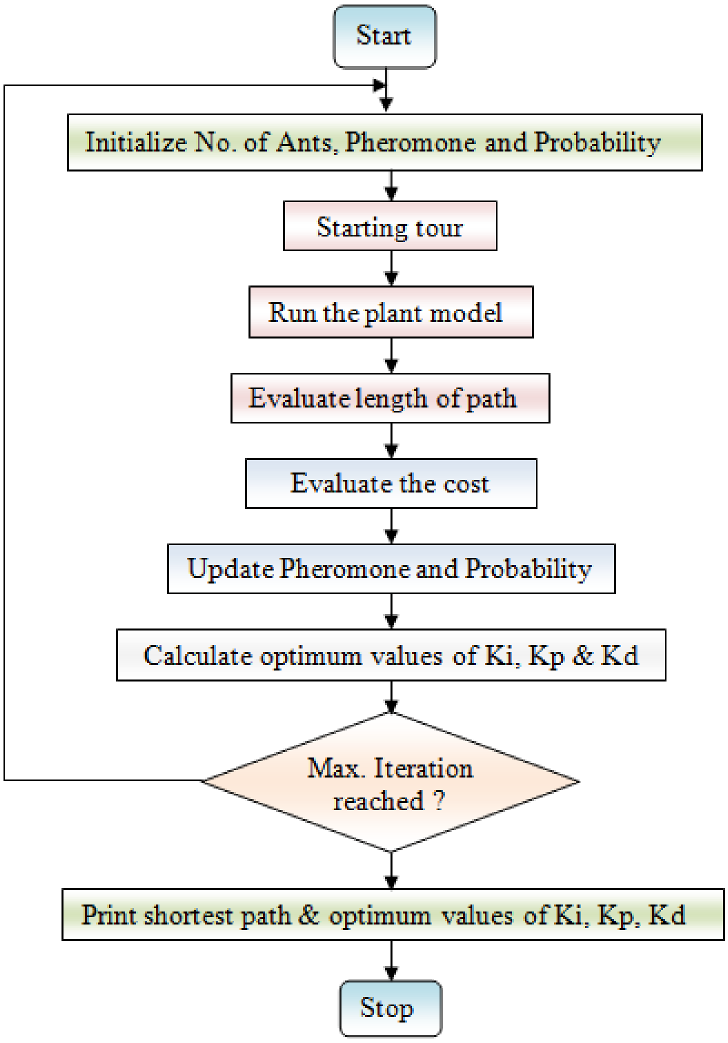


Fig. 3. Flowchart of Ant Colony Optimization tuning

C. Proposed Tuning Method

The Pattern Search (PS) optimization technique is a derivative free evolutionary algorithm suitable to solve a variety of optimization problems that lie outside the scope of the standard optimization methods. It possesses a flexible and well-balanced operator to enhance and adapt the global search and fine tune local search. In this paper Pattern search toolbox is used. The Pattern search toolbox is powerful toolbox which developed by Professor Dingyu Xue in 2012 [12]. This toolbox can be downloaded from the Math Works website, in the "MATLAB file-exchange" pages. By typing optimpid in command window, it shows an icon on command window as shown in Figure 4. The plant model should be created before the interface can be used. The 'Controller type' specifies the type of controller. The available controller structure can be selected from the '*P/PI/PID/PD*' controllers list. The '*Show file*' button displays the objective function generated. The following steps are used to design a controller:

- Enter the Simulink file name in the edit box ‘ *plant model name*’ or the plant model can be specified with the dialog box brought in by the file opening icon.
- Edit the simulation time t_s in ‘*Terminate time*’ edit box.
- Click on ’Create files’ button to generate the objective function in MATLAB.
- Now click on ‘*Optimize*’ button to design the controller.

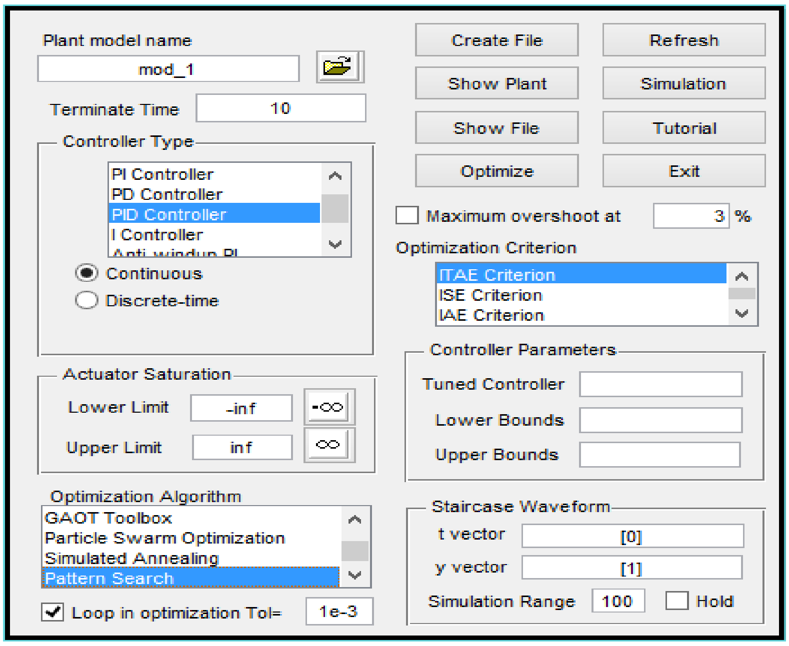


Fig. 4. PID controller Optimizer using Pattern Search Toolbox

The following steps are used to design the controller

Enter the Simulink file name in the edit box ‘ *plant model name*’ or the plant model can be specified with the dialog box brought in by the file opening icon.

- Edit the simulation time t_s in ‘*Terminate time*’ edit box.
- Click on ’Create files’ button to generate the objective function in MATLAB.
- Now click on ‘*Optimize*’ button to design the controller.

The button ‘*Show Model*’ is used to show the plant model in Simulink. The ‘*Show file*’ button displays the objective function generated.

The gains of controller are shown in Table II. The Performance Index of above controller is obtained using Integral of Time multiply Absolute Error (ITAE) of deviations of frequency and tie-line power of all area were considered as objective function. Accordingly, the objective function is defined as (t_s is the simulation time).

$$J = \int_0^{t_s} t(\Delta f_i + \Delta P_{tieij})^2 \, dt \qquad \text{where } i = 1, 2 \text{ and } 3;\ j = 1, 2 \text{ and } 3 \text{ but } j \neq i$$

TABLE II. Gain values of PID controller with various tuning algorithms in all areas.

Area-i	Refined Z-N			Ant Colony Optimization			Pattern Search		
	K_P	K_I	K_D	K_P	K_I	K_D	K_P	K_I	K_D
Area-I	6.0241	3.6946	0.9717	7.5762	6.9697	1.7050	14.1607	17.9244	6.2195
Area-II	2.7969	3.7178	0.4173	4.1053	5.8268	1.7050	2.7660	8.8002	1.0729
Area-III	5.7858	3.7821	0.9095	7.8330	6.9697	1.5986	12.4074	16.877	4.6455

ISSN (Print) : 2319-8613
ISSN (Online) : 0975-4024

IV. SIMULATION RESULTS

The conventional interconnected power system is modified with Reheat thermal turbine and DEG in Area-I, Non-reheat thermal turbine with Generation Rate Constraint (GRC) in Area-II and Reheat thermal turbine and BESS in Area-III. This hybrid electric power system was simulated under different load disturbances such as Step load, Random load variations. The validity and performance of proposed controller was evaluated for minimization of frequency and tie line power deviations in hybrid electric power system.

A. Illustration-I

Step Load disturbances: To study the dynamic performance of proposed controller, a step increase in load (ΔP_L) of 1% and wind power variations (ΔP_{WTG}) of 0.01pu are applied to interconnected hybrid electric system with GRC and without/with BESS. The Fig. 5(a) to Fig. 5(c) and Fig. 6(a) to Fig. 6(c) respectively shows the change in frequency(df) and Tie line active power variations (dPtie) of interconnected hybrid electric power without energy storing element, BESS (with GRC). Similarly the Fig. 7(a) to Fig. 7(c) and Fig. 8(a) to Fig. 8(c) respectively shows the change in frequency(df) and Tie line active power variations (dPtie) of interconnected hybrid electric power with energy storing element(BESS) and GRC. From the results, with Pattern Search algorithm, the frequency deviations of system are quickly damped with comparatively reduced negative overshoot.

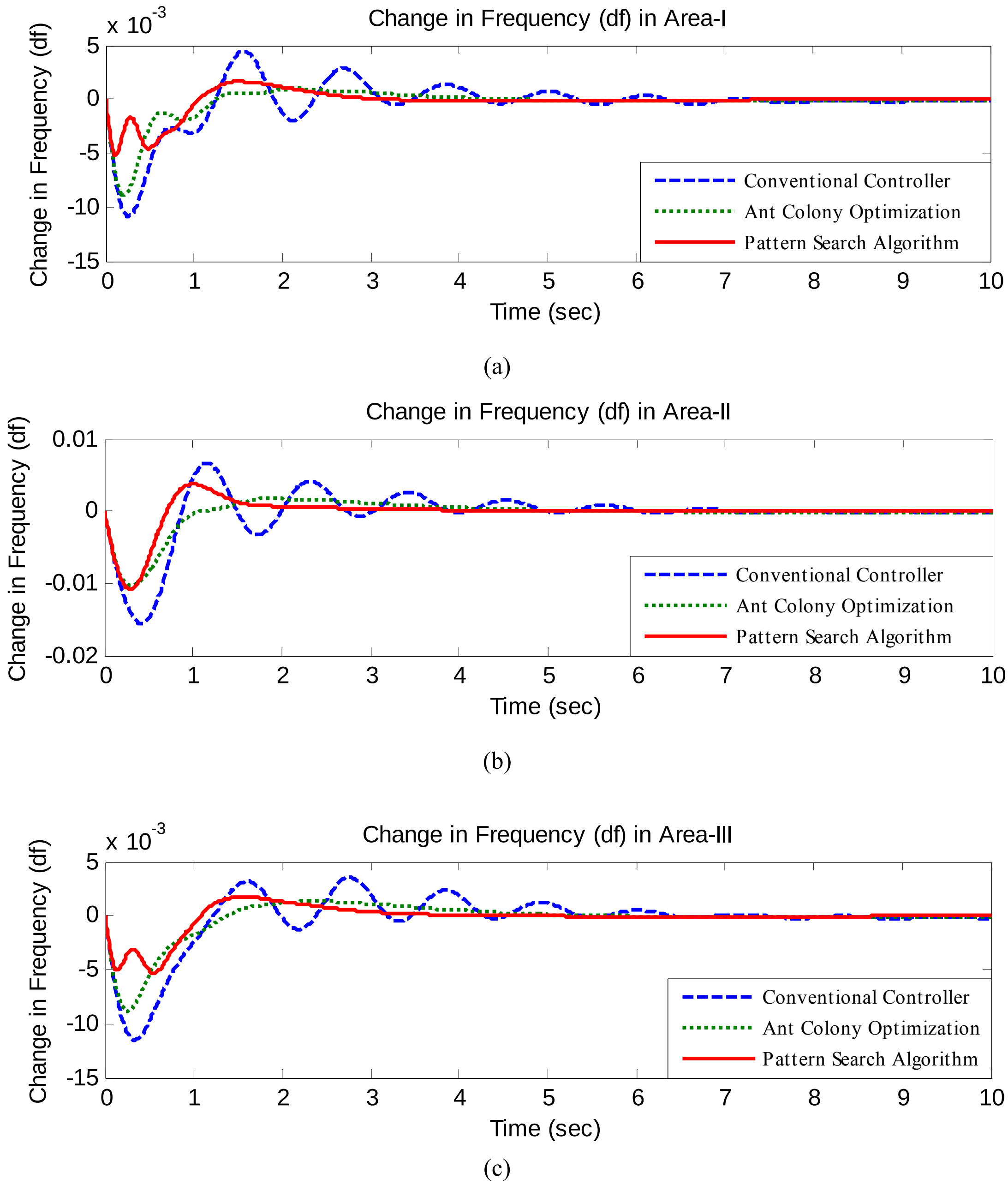
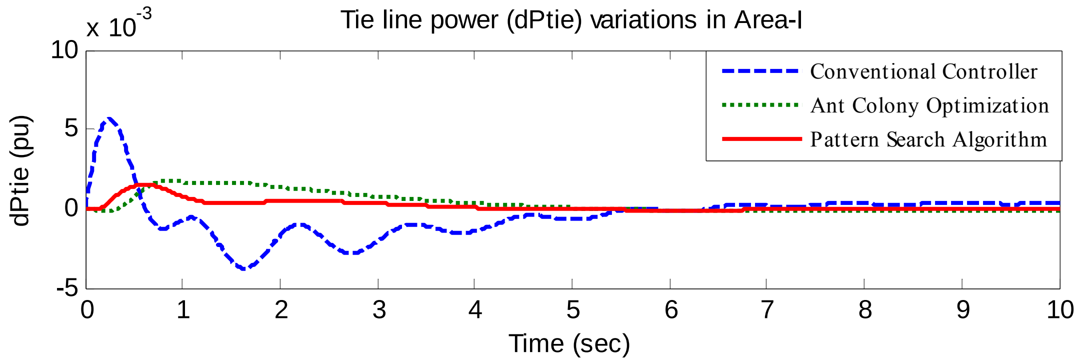
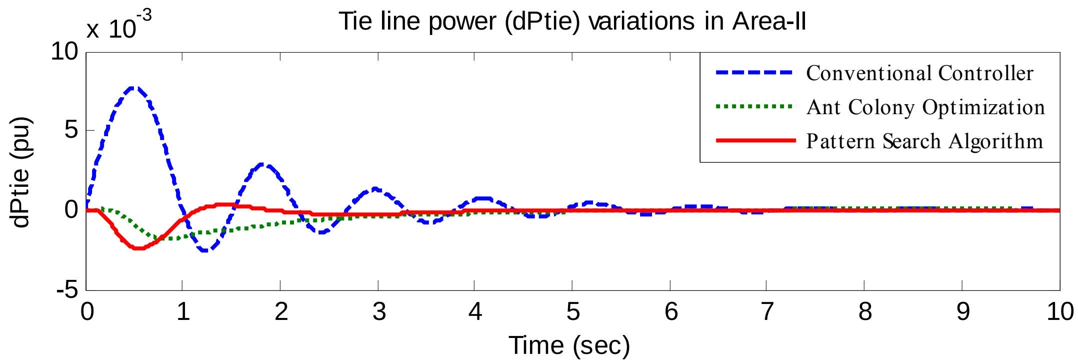


Fig. 5. Change in frequency (df) without Energy Storing System (BESS)



(a)



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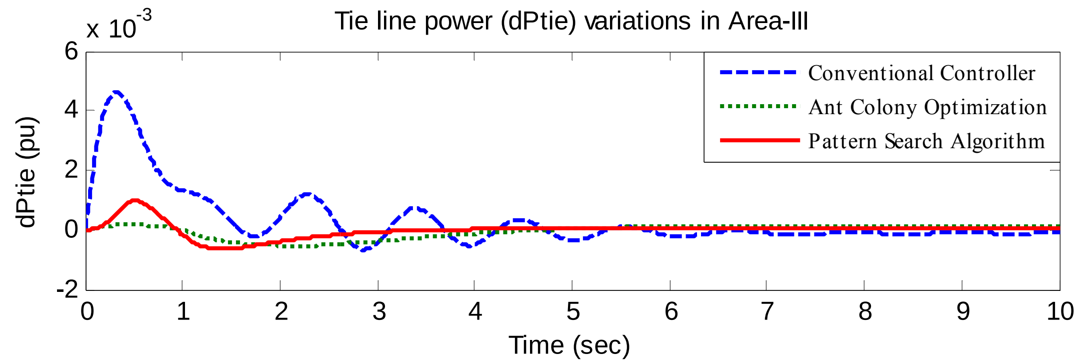

(c)

Fig. 6. Change in frequency (df) with Energy Storing System (BESS)

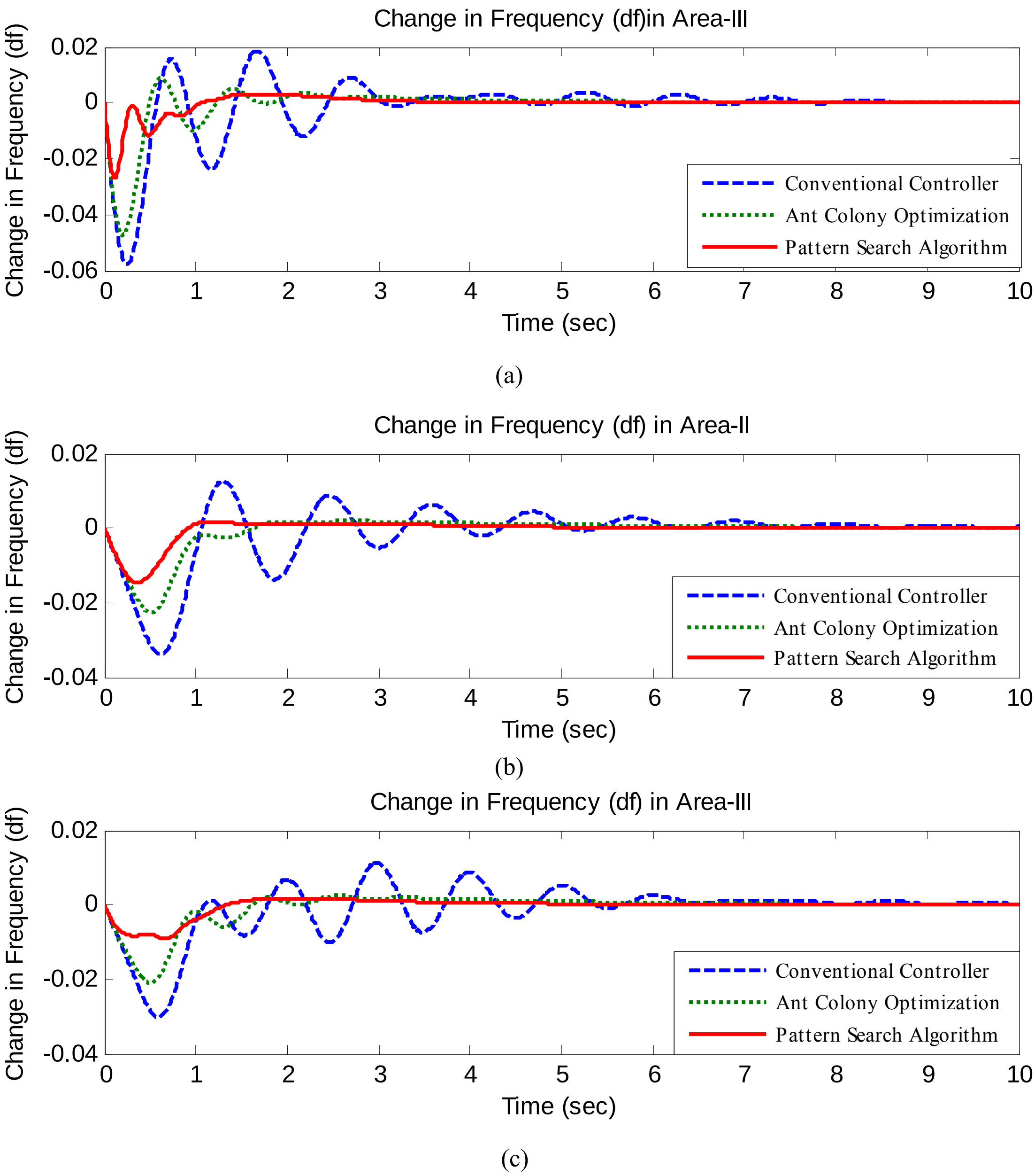

Fig. 7. Tie line Power (dPtie) variations without Energy storing System (BESS)

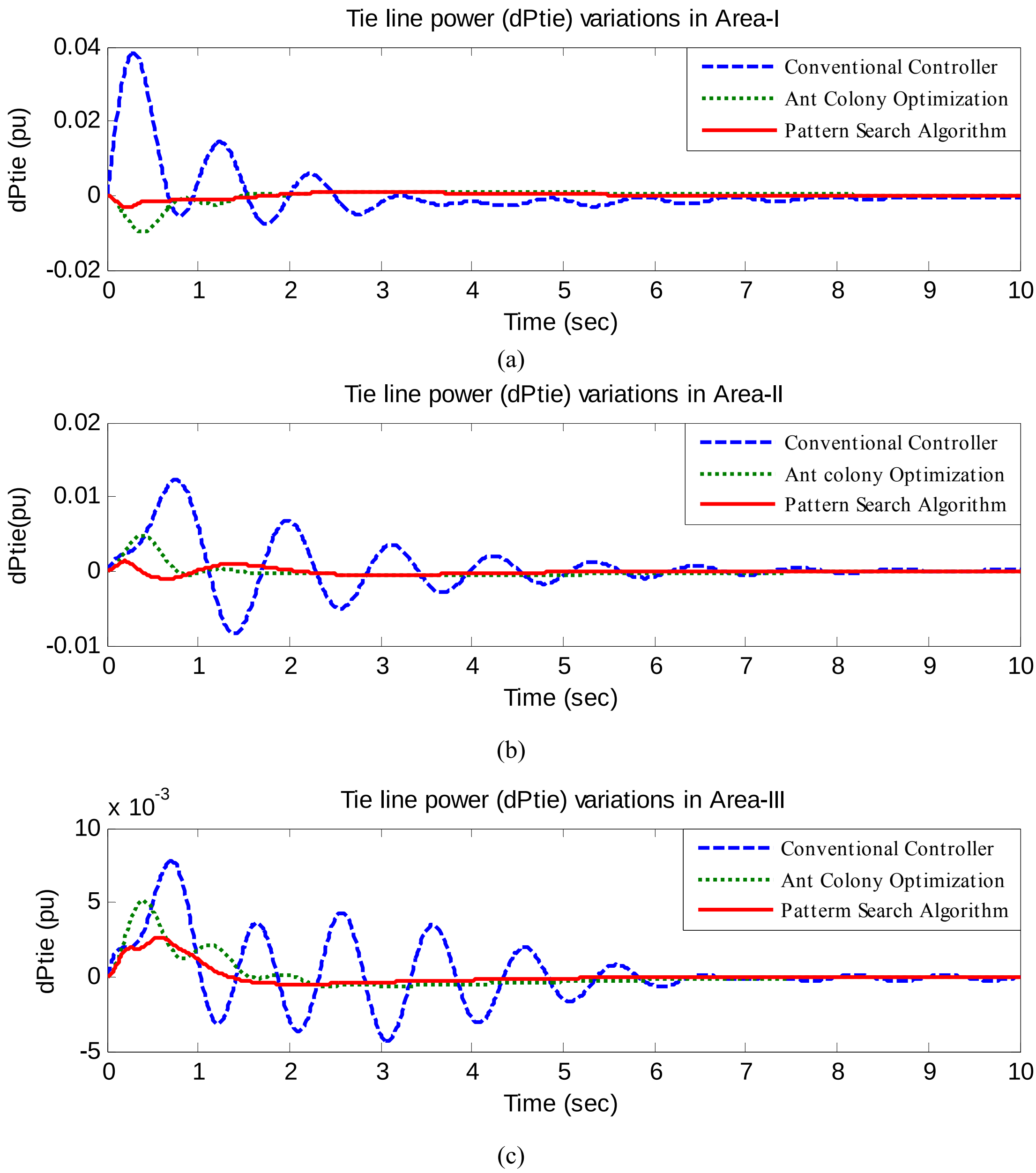

Fig. 8. Tie line Power (dPtie) variations without Energy storing System (BESS)

B. Illustration-II

Random Load disturbances: To study the validity and effectiveness of the proposed controller, the same hybrid electric system with controller and without/with BESS was checked for random wind power input (weather conditions as input disturbances) with increase in load disturbances (ΔP_L=0.01pu) in all areas. The Fig. 9(a) to Fig. 9(c) indicates the change in frequency (df) without BESS. Similarly, the Fig. 10(a) to Fig. 10(c) shows the change in frequency (df) with BESS. The results indicates that with proposed Pattern search controller, the frequency oscillations are reduced significantly and gives robust performance against stochastic variations in wind power due to weather conditions.

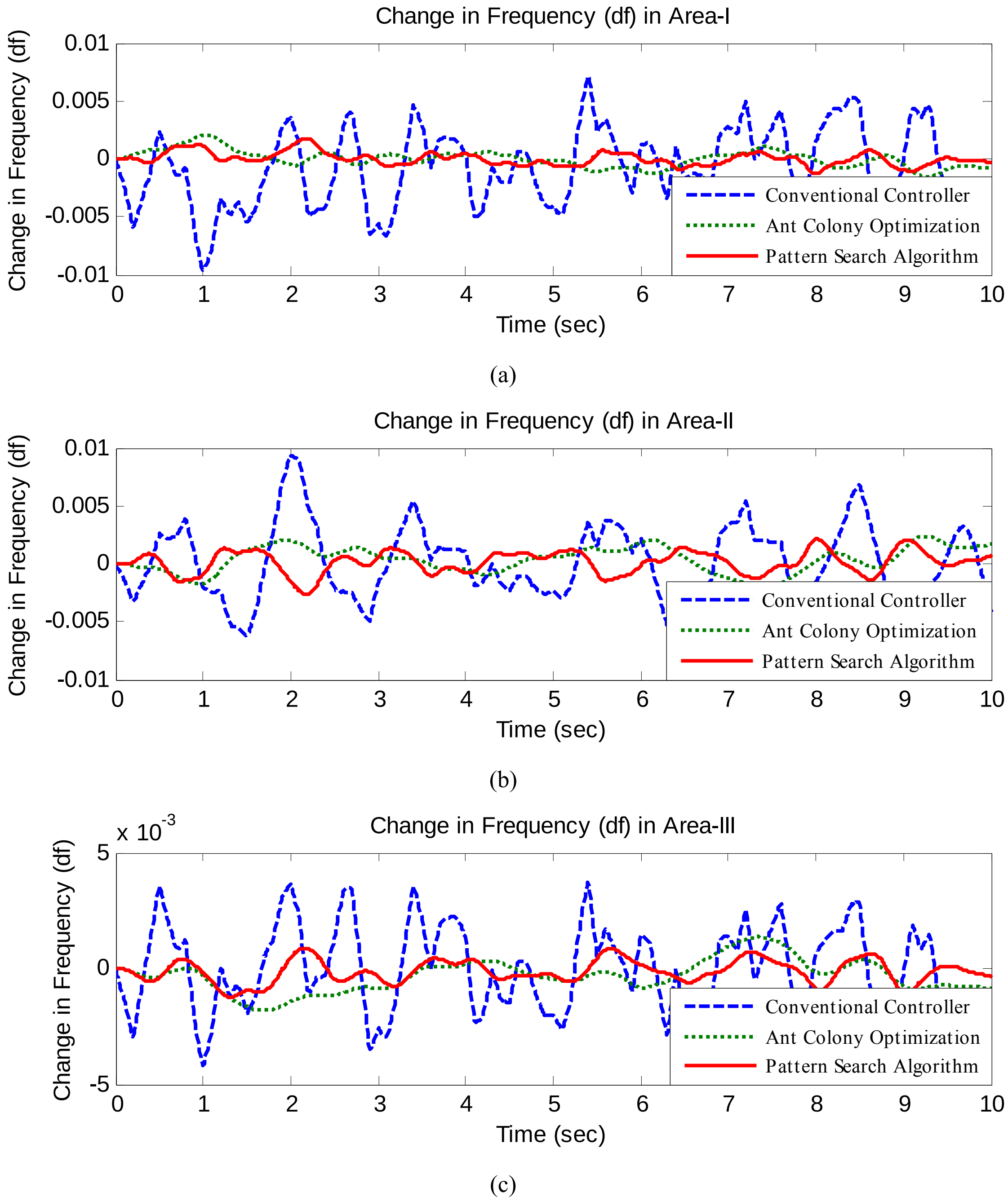

Fig. 9. Change in frequency (df) without Energy Storing System (BESS)

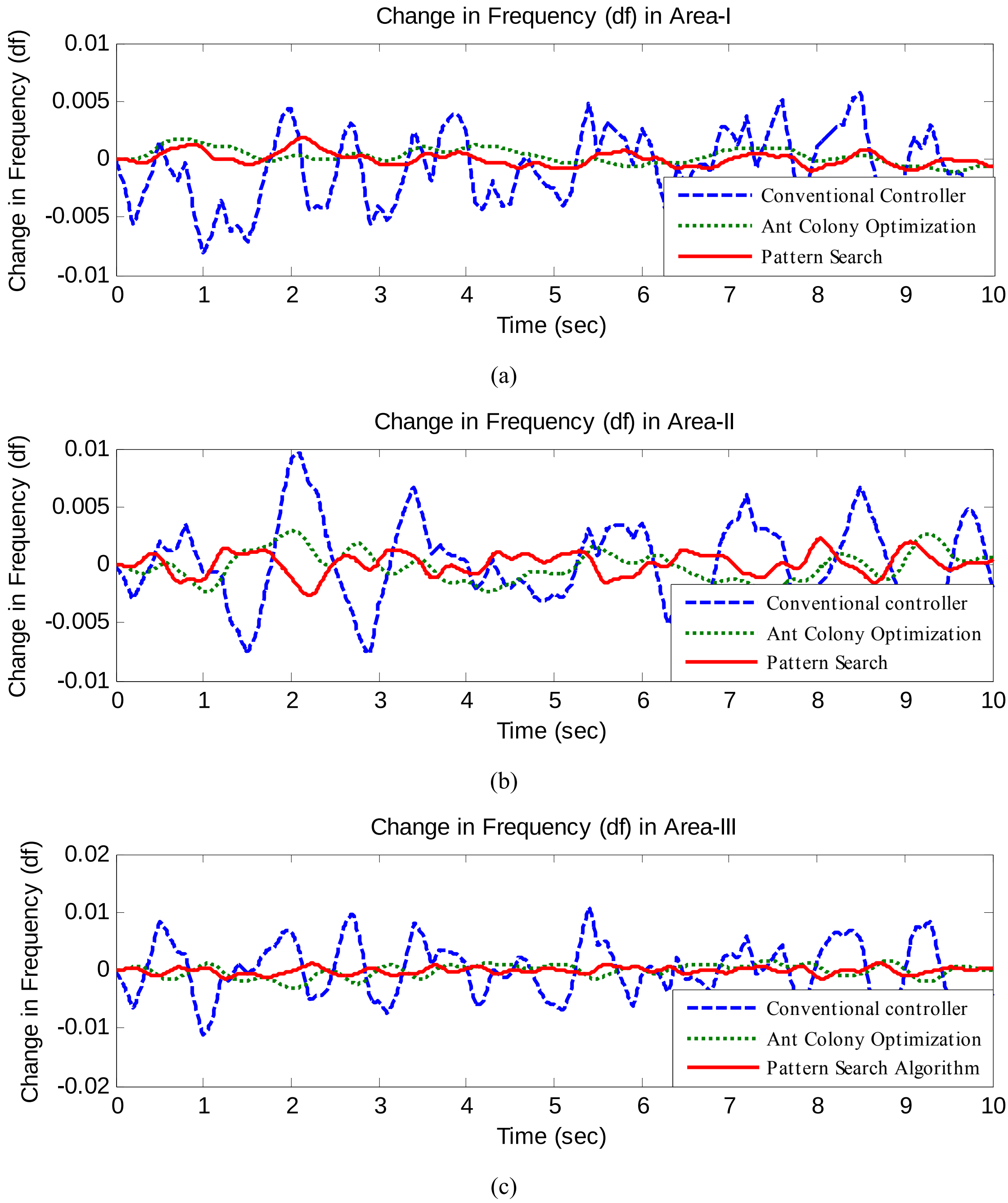

Fig. 9. Change in frequency (df) with Energy Storing System (BESS)

V. CONCLUSIONS

This paper has presented the time domain simulations for load frequency control of hybrid electric system consisting of offshore wind form (WTG), Energy staring element (BESS) and GRC of turbine. In order to eliminate the mismatch in supply and demand under varying condition of load and generation i.e to reduce the frequency deviations, the output power from the sources is regulated using the PID controllers. The performance of the each controller is examined from dynamic behavior in time domain simulations of hybrid Electric system.

It has been observed from results that the Pattern Search controller illustrates superior control effort and guaranteed robust performance as compared to conventional and Ant Colony optimization controller, against various uncertainties such as wind power variations and various load conditions. Finally, it can be concluded from the simulation results that the Pattern Search controller has good effectiveness on minizing the frequency variations and enhancing the closed loop stability.

APPENDIX

TABLE III. Parameters of studied Wind generator & Energy storing element.

K_{WTG} = 1.0 and T_{WTG} = 1.5Sec	K_{BESS} = -1/300 and T_{BESS} = 0.1 Sec

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