Secondary Frequency Regulation of Multi-area Interconnected Hybrid Power System with Electric Vehicle

Pushpa Gaur[1], Nirmala Soren[1], and Debashish Bhowmik[2]

[1]Electrical Engineering Department, National Institute of Technology Silchar, Assam, India
[2]Electrical Engineering Department, Tripura Institute of Technology Narsingarh, Agartala, Tripura, India

Abstract: In modern power system, plugged in electric vehicle plays a very vital role in regulation of system frequency as it is a form of battery energy storage system. This paper presents an aggregate model consisting of a three area system embedded with electric vehicle (EV) in all the three control areas along with Dish-Stirling solar thermal system (DSTS) in only Area-1. The thermal systems are provided with single reheat turbine, governor dead band and generation rate constraint of 3% per minute to give a more realistic view to the designed system. Two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controller with filter is applied as secondary controller in all the three control areas. Maiden application of a new nature inspired optimization technique called Wind Driven Optimization technique in load frequency control is made in this paper. A comparison is done between 2DOF-PID and Proportional-Integral-Derivative (PID) controller to verify the effectiveness of the former. Analysis reveals the advantage of including DSTS in the aggregate model which proves the role of renewable energy sources in overcoming the fluctuations in frequency and tie-line power in a power system under both nominal 1% step load perturbation and random load perturbation. An attempt has also been made to show the impact of incorporating EVs under nominal system condition into the system, and it has been observed that the number and magnitude of oscillations are decreased to great extent with its incorporation.

Keywords: Electric vehicle, load frequency control, 2DOF-PID controller, Wind driven optimization, Dish-Stirling solar thermal system.

1. Introduction

Load frequency control (LFC) is a very important arena of research which mainly serves the objectives of maintaining the system frequency and the tie-line power interchange within permissible limits. There are many sources of electrical power generation, also called conventional sources of power generation, like thermal and hydro. The researchers are concerned regarding certain major issues like depleting quantity of fossil fuels and also environmental hazards caused due to the their consumption. These reasons force the researchers to divert their attention more towards the usage of some alternative eco-friendly sources of energy like solar, wind, ocean thermal energy, etc. Many distributed generation sources are also available like aqua electrolyser, battery energy storage sources (BESS), etc., which may serve the purpose of feeding local load demand. Nowadays, electric vehicles (EVs) are also considered as a type of BESS which are capable of storing electrical energy in the form of charge in the battery which may be integrated to the conventional power grid to supply the increasing demand.

There is huge research going on in the area of LFC, the basic model of which was first introduced by Elgerd [1, 2] and carried forward by many other researchers. The power system engineers try hard to maintain the balance between generation and demand so as to retain constant frequency and tie-line power exchange between the interconnected areas [3]. There are many types of system taken under consideration like thermal system, hydro system, etc. [4, 5]. Nowadays the concept of multi-source power system has also come into existence and introduced in LFC by many researchers [6, 7]. However, taking the environmental issues into

consideration, the authors are shifting their interest towards more and more incorporation of renewable energy sources (RES) into power system for electric power generation. One such source of power generation is solar power which is trapped through the idea of Dish-Stirling solar thermal system, which is presented by the authors in [8-10]. Utilization of EVs for LFC in an interconnected power system has been done and available in many recent literatures [12-14]. But, the researchers have not studied the impact of incorporating both RES and EVs in a system, and hence, it provides a scope for further studies.

The applications of different types of controllers have been made in the past literatures. The authors in [15] applied conventional integer order single degree of freedom controller for investigation. The authors in [16] introduced another controller called two degree of freedom Proportional-Integral controller, whose implementation in LFC studies in the form of two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controller has been done by Sahu et al [17]. Artificial intelligence (AI) such as fuzzy logic and neural network has also played a vital role in deriving new controllers and the application of the controllers have been made by the authors in [18-19]. But the computation time required in AI inspired controllers is more which discourages its large scale usage. Whereas, 2DOF-PID controller gives excellent results, and hence, encourages its application in different types of interconnected system.

The controllers have a number controlling parameters which need to be optimized so that they can be set to encounter the fluctuations in the system conditions. Many researchers have employed different optimization techniques in LFC like artificial bee colony [20], particle swarm optimization [21], firefly algorithm [22], genetic algorithm [23] and bacteria foraging [24] for optimization of controller parameters. Another optimization technique called Wind driven optimization was introduced in [25], and its application in the area of electromagnetics was made. But its utility in the field of LFC is still unexplored, and hence needs attention.

On the basis of the intensive survey carried out above, the objectives of this work are fivefold.
1) Design of a multi-area system with the incorporation of renewable energy source (Dish-Stirling solar thermal system) and electric vehicle
2) Application of 2DOF-PID controller in the system designed and its comparison with PID controller to find the best controller.
3) Application of Wind Driven optimization for simultaneous optimization of the gains and parameters of the controllers.
4) Impact evaluation of introducing Dish-Stirling solar thermal system in the system under both step load and random load perturbation.
5) Impact assessment of embedding electric vehicle in the system.

The rest of the paper is organized as follows. Section 2 explains the system considered for investigation, the controller used and the optimization used for optimizing the controller gains. Section 3 discusses about the various results and analysis carried out, and finally, Section 4 summarizes the conclusion the work.

2. Methodology applied
The following methodologies are applied in order to fulfil the objectives mentioned above.

A. System under investigation
Investigation is carried out on an unequal three area thermal system having generating capacity in the ratio 1:2:4 for Area-1:Area-2:Area-3. The system considered consists of a renewable energy source (RES) called Dish-Stirling solar thermal system (DSTS), a thermal unit and an electric vehicle (EV) fleet in Area-1. Each Area-2 and Area-3 includes a thermal plant and EV fleets. The power generating capacity of Area-1 is 2000 MW, of Area-2 is 4000 MW and that of Area-3 is 8000 MW. In the power generation of a particular area of the system considered, different generating units are contributing, the participation factor of which are set denoting how much is the share of the units out of the total generations. $K_{DS} = 0.1$ is the

participation factor of DSTS unit, $K_{EV} = 0.1$ is the participation factor of EV fleet and $K_T = 0.8$ in Area-1 and $K_T = 0.9$ in Area-2 and Area-3 are the participation factors of the thermal units. The thermal units are incorporated with single reheat type turbine, generation rate constraint of 3% per minute and governor dead band of 0.06% is considered in all the three areas for the thermal units to give a more realistic view to the system. The transfer function model for the system with DSTS and EV is given in Figure. 1. The objective function is taken as an Integral squared error (ISE) and is given by equation (1).

$$J = \int_0^T \left\{ \left(\Delta f_i\right)^2 + \left(\Delta P_{tiej-k}\right)^2 \right\} dt \tag{1}$$

Where, Δf_i is the frequency deviation in area-i and ΔP_{tiej-k} is the deviation in tie line power in tie connecting area j and k.

In Figure 1, T_g, T_t and T_r are the time constants of governor, turbine and reheat of the thermal system, K_r is the reheat coefficient, T_p and K_p are the time constant and gain of power system. T_{DSTS} and K_{DSTS} are the time constant and gain of DSTS unit included in the system under study, respectively. R is the governor droop equal to 2.4 HZ/pu MW. The analysis is carried out under nominal system condition taken from [20], that is, 50% loading; disturbance is 1% step load perturbation (SLP) and inertia constant (H) is taken as 5s. The transfer function for DSTS is given in [10].
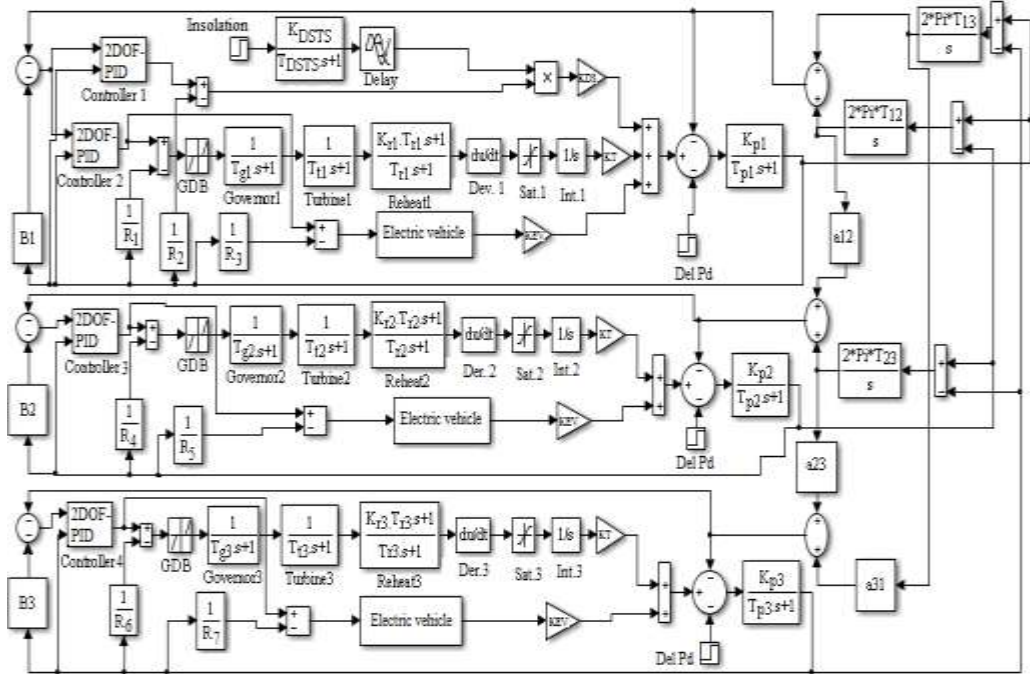

Figure 1. Transfer function model of three area system with DSTS and EVs

With the depletion in the reserve of fossil fuels, researchers are moving towards more and more utilization RES, one of which is DSTS. It works on the principle of grabbing solar energy and converting it into electrical power. DSTS consists of a parabolic dish, with a receiver implanted on the focus of the parabolic dish and a tracking device. The sunrays are made to concentrate on the focus which consists of a working fluid. The energy trapped from the sun is utilized to heat the fluid, which will in turn drive the Stirling engine coupled to the generator, hence producing electrical energy. The transfer function of DSTS is given in equation (2).

$$\frac{K_{DSTS}}{1 + sT_{DSTS}} \tag{2}$$

The transfer function model of EV is given in Figure. 2. EV is a very good example of battery energy storage system, which is nowadays highly employed by the researchers. The

energy stored in the batteries of the EVs will help the system restore its nominal frequency on the occasion of load fluctuations in the power system by serving the load demand.
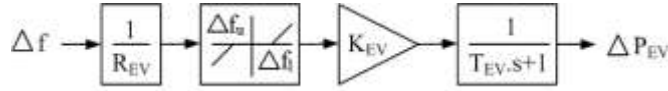

Figure 2. Transfer function model of Electric Vehicles

The transfer function of EV is given in equation (3).

$$TF_{EV} = \frac{K_{EV}}{1 + sT_{EV}} \tag{3}$$

$$ACE = B\Delta f + \Delta P_{tie} \tag{4}$$

The inputs to the system are the controller input, disturbance in change in load and change in tie-line power, whereas the outputs are deviation in frequency and area control error (ACE) given by equation (4), where, B denotes frequency bias.

B. Two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controller

Two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controller is a two input one output controller which have two set point variables, namely, proportional set point and derivative set point. Degree of freedom signifies the number of closed loop transfer functions that can be adjusted. The schematic diagram of 2DOF-PID controller with filter coefficient is shown in Figure. 3, where R(s) and Y(s) refer to the two inputs, U(s) is the output, and N is the filter coefficient. PSW and DSW are proportional set-point weight and derivative set-point weight, respectively. K_p, K_i and K_d are the proportional, integral and derivative gains of 2DOF-PID controller. There are five parameters of 2DOF-PID controller that can be adjusted, PSW, DSW, K_p, K_i and K_d. 2DOF-PID controller evaluates the difference between weighted signals depending on the two set point weights for proportional, integral as well as derivative actions.
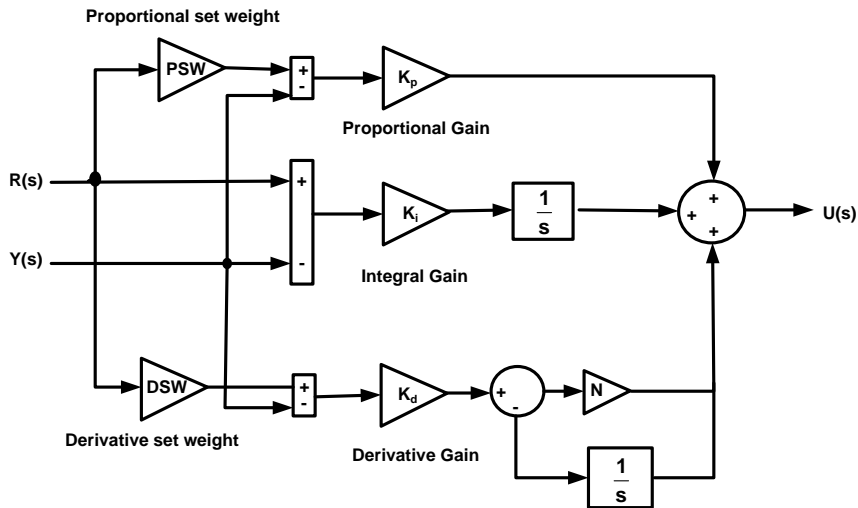

Figure 3. Schematic diagram of Two Degree of Freedom Proportional-Integral-Derivative (2DOF-PID) Controller

There are many objective functions available in the literature like Integral Squared Error (ISE), Integral Time Squared Error, Integral Absolute Error, and Integral Time Absolute Error. In order to design a controller based on optimization technique, it is necessary to choose an

appropriate objective function, founded on the performance criteria depending on the system responses, namely, peak overshoot, rise time, settling time, and steady state errors. In power system, oscillations caused in the system due to variations in load demand have to be died out at the earliest. ISE integrates the square of the error over time due to which it can eliminate large errors quickly which results in fast response, hence, in the present work ISE has been chosen as objective function. The value controller gains and other parameters should be small enough to ensure that the area generators are not chasing load deviations of small time durations.

C. Wind Driven Optimization Technique

A novel meta-heuristic algorithm inspired by nature called Wind Driven Optimization (WDO) has been proposed by the authors in [25]. The wind blows from high pressure region to low pressure region in order to balance the air pressure in our atmosphere with a speed relative to the pressure gradient. Taking assumptions of hydrostatic air balance and vertical movement is weaker than the horizontal movement, the change in pressure as well as the motion of wind can be taken as a horizontal movement. Although, our world is a three-dimensional, the motion of wind takes into account addresses multi-dimensional problems. Furthermore, to derive the operators employed in WDO algorithm, specific assumptions and simplifications are required. The algorithm initializes with Newton's second law of motion that offers very precise results when utilized to analyse the motion of wind.

$$\rho a = \sum F_i \tag{5}$$

Where, the air density is denoted by ρ, a denotes the acceleration vector, and the forces acting on the mass are denoted by F_i. The relation between air pressure, density and temperature is given by:

$$P = \rho RT \tag{6}$$

Where, pressure is denoted by P, universal gas constants denoted by R and temperature is denoted by T.

The motion of wind in any specific path is controlled by four main factors, as specified by equation (5), out of which the most dominant force that helps in the movement of air is the pressure gradient force (F_{PG}), whereas the friction force (F_F) opposes such movement, and is given by equation (7). Gravitational force (F_G) pulls the particles in the direction of the origin of the coordinate system. Another force called Coriolis force (F_C) happens due to rotation of earth and causes the movement of wind from one dimension to another. The implementation of WDO as the movement in one dimension influences the speed in another.

The equations defining the forces are given below, where δV denotes an infinitesimal air volume. Rotation of the earth is represented as Ω represents the, gravitational acceleration is denoted by g, and velocity vector of the wind is denoted by u.

$$F_F = \rho \alpha u \tag{7}$$

$$F_G = \rho \delta V g \tag{8}$$

$$F_C = -2\Omega * u \tag{9}$$

$$F_{PG} = -\nabla P \delta V \tag{10}$$

All the above equations defining forces may be added up and put in the right-hand side of the Newton's second law of motion. The equation formed is given below:

$$\rho \Delta u = \left(\rho \delta V g \right) + \left(-\nabla P \delta V \right) + \left(-\rho \alpha u \right) + \left(-2\Omega * u \right) \tag{11}$$

The velocity update equation can be derived from the above equation by considering an infinitesimal air particle that moves with the wind. The pressure in equation (6) can be substituted in place of ρ and an assumption of time step to be unity ($\Delta t = 1$) is taken which gives the velocity update equation:

$$u_{new} = \left(1-\alpha\right)u_{cur} - gx_{cur} + \left(\frac{cu_{cur}^{other\ dim}}{P_{cur}}\right) + \left(\frac{RT}{P_{cur}} \mid P_{opt} - P_{cur} \mid \left(x_{opt} - x_{cur}\right)\right) \qquad (12)$$

The updating of the location of air parcels and their velocity is done in each iteration which is done by using equation (12) whereas updating their position is done by employing the below equation:

$$x_{new} = x_{cur} + \left(u_{new}\Delta t\right) \qquad (13)$$

Algorithm applied in this paper is shown below:
1. Initialize population size, maximum number of iterations, coefficients, boundaries and pressure function definition.
2. Assign random position and velocity.
3. Evaluate the pressure for all the air parcel.
4. Update velocity and check for its limits.
5. Update position and check for boundaries
6. If the maximum number of iterations is reached, then stop, otherwise go to step 3.

3. Analysis and results
A number of case studied have under different system conditions been done to analyze the system under consideration and also to analyze the impact of introducing RES and EV in the conventional three area thermal system.

### A. Under nominal system condition
In this section, the analysis is carried out under nominal system condition of 1% step load perturbation (SLP), 50% loading and inertia constant (H) is 5s.

1). Performance comparison of dynamic responses of 2DOF-PID controller with PID controller with 1% SLP
The investigated system consists of two degree of freedom Proportional-Integral-Derivative (2DOF-PID) as secondary controller in all the three control areas, gains and other parameters are optimized by Wind driven Optimization (WDO) Technique. To investigate the best controller among classical Proportional-Integral-Derivative (PID) controller and 2DOF-PID controller, PID controller gains are also optimized using WDO technique and the responses are plotted. A comparison is shown in Figure 4. between the responses obtained by using 2DOF-PID and PID controller which reveals the superior performance of 2DOF-PID over PID in terms of both settling time and magnitudes of oscillation. Table 1 displays the value of the optimized controller gains and other parameters of both 2DOF-PID and PID controller.

Table 1. Optimum values of gains of PID and 2DOF-PID controller

| Controller	Gains	Optimum values			
		Controller 1	*Controller 2*	*Controller 3*	*Controller 4*
2DOF-PID	K_{Pi}^*	1.222998	1.329431	1.139990	1.954123
	K_{Ii}^*	0.704561	0.349805	1.002502	1.590770
	K_{Di}^*	1.258803	0.948007	0.807787	1.787129
	b_i^*	0.125872	1.655996	1.705142	0.975410
	c_i^*	0.541114	1.732121	0.909218	0.486881
PID	K_{Pi}^*	1.223857	0.088659	0.771241	1.183774
	K_{Ii}^*	0.362512	1.151877	1.351085	1.484348
	K_{Di}^*	1.017773	0.114936	1.424268	0.481735
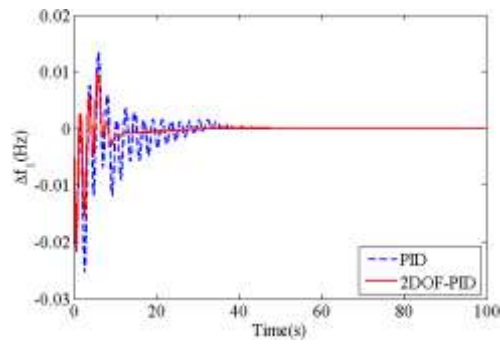
(a)
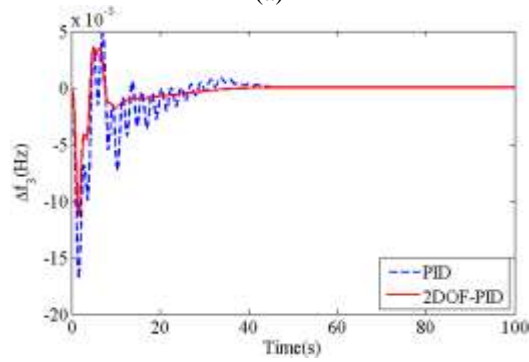
(b)
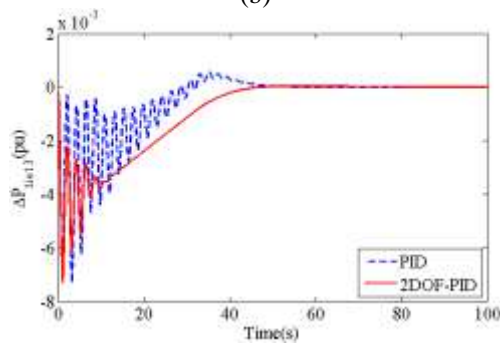
(c)
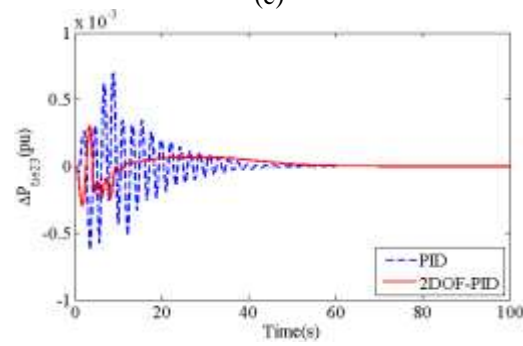
(d)

Figure 4. Comparison of change in frequency and tie-line power of 2DOF-PID with PID controllers under 1% SLP (a) Δf_1-t, (b) Δf_3-t, (c) ΔP_{tie13}-t and (d) ΔP_{tie23}-t.

Table 2. Values of settling time, peak overshoot and peak undershoot

	Controller	Figure. 4(a)	Figure. 4(b)	Figure. 4(c)	Figure. 4(d)
Settling time(s)	2DOF-PID	31.6	36.21	46.39	53.45
	PID	43.04	45.85	49.04	58.37
Peak overshoot	2DOF-PID	0.009521	0.00352	0.0000047	0.0003001
	PID	0.0133	0.004828	0.0005653	0.0006936
Peak undershoot	2DOF-PID	0.02082	0.01112	0.007247	0.0002765
	PID	0.02507	0.01662	0.007245	0.0006013

2). Comparison of dynamic responses of 2DOF-PID controller with and without DSTS with 1% SLP

Section 1) implies that 2DOF-PID controller outperforms PID controller in terms of settling time and number of oscillations, which proves that the former is best for the system under consideration. So, for this analysis 2DOF-PID is chosen as the secondary controller. In this section, an analysis is carried out to find out the significance of incorporating DSTS in the system. For this purpose, a comparison is shown in Figure. 5 between the dynamics obtained with and without DSTS in the system. From the Figures given above, it can be clearly observed that there are fewer oscillations in the system with DSTS than that without DSTS, and also, the settling time is less with DSTS.
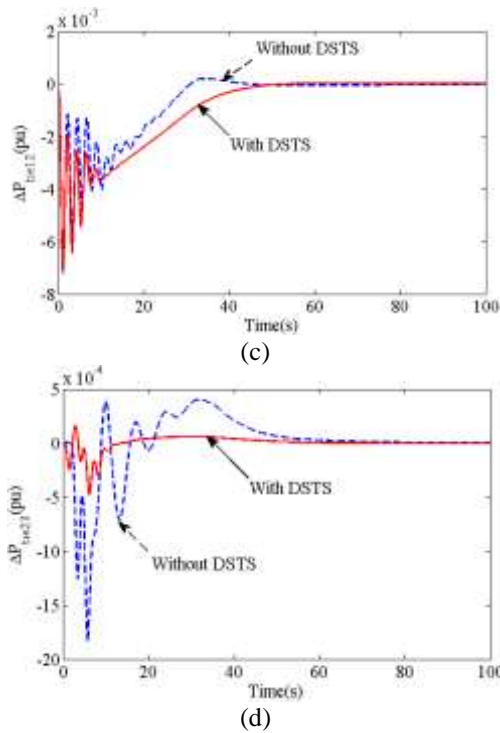

(a)

(b)

(c)

(d)
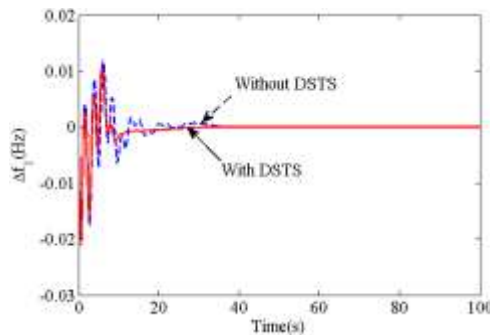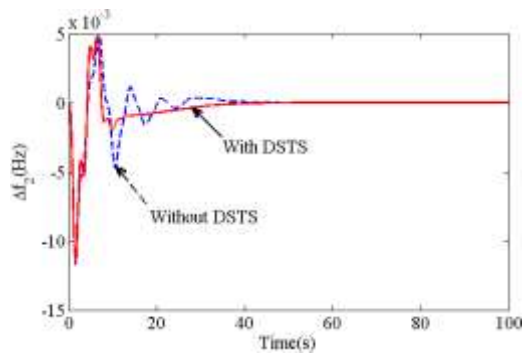
Figure 5. Comparison of dynamic responses with and without DSTS under nominal system conditions (a) Δf_1-t, (b) Δf_2-t, (c) ΔP_{tie12}-t, and (d) ΔP_{tie23}-t.

B. Under random loading condition

In Section A, step load perturbation (SLP) is used as disturbance, which is replaced by random load perturbation (RLP) in this section and further analysis is carried out.

1). Performance comparison of responses for 2DOF-PID and PID controller

The 2DOF-PID controller is used as secondary controller for the three area system included with DSTS in Area-1and EVs in all the three areas. An investigation is carried out for finding the best controller among 2DOF-PID and PID controller under scenario of RLP. The RLP pattern applied to the system is shown in Figure.6a. The corresponding dynamic responses obtained for both the controllers are obtained and compared, as shown in Figure.6b, Figure.6c and Figure.6d. The comparison reveals that 2DOF-PID controller behaves much better than PID controller even under random loading condition.
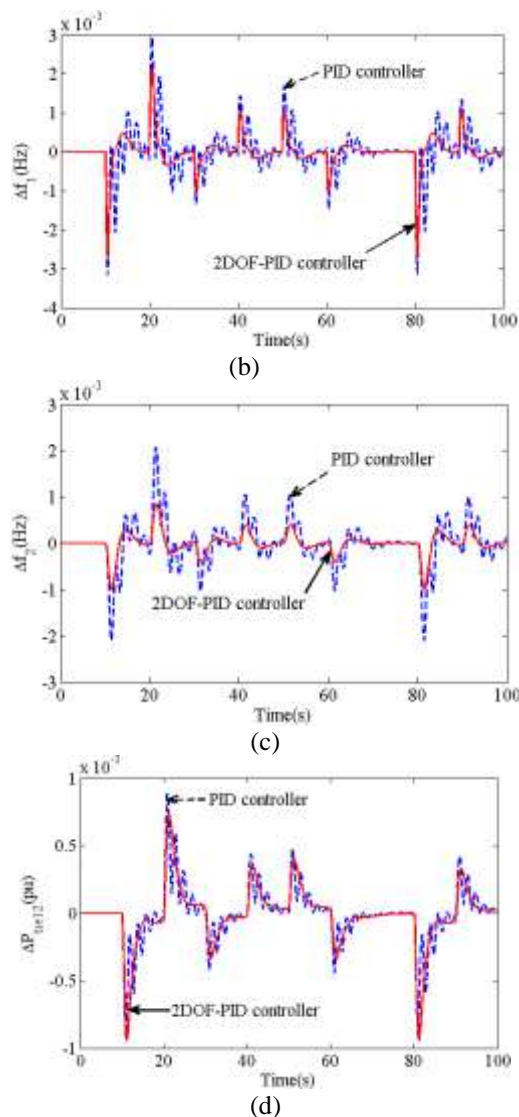

(a)
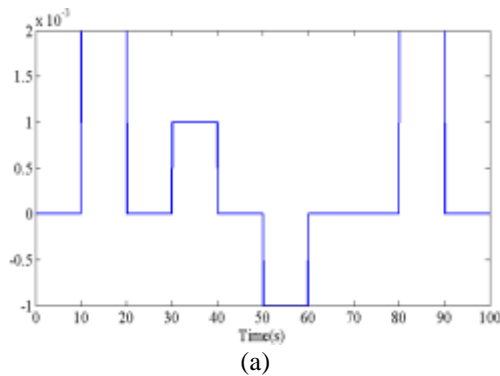
Figure 6. (a) Random load pattern, (b) Comparison of Δf_1 vs. t with 2DOF-PID and PID controllers, (c)Comparison of Δf_2 vs. t with 2DOF-PID and PID controllers, and (d) Comparison of ΔP_{tie12} vs. t with 2DOF-PID and PID controllers

2). Comparison of responses for 2DOF-PID controller with and without DSTS

The investigations carried out above exposed that 2DOF-PID controller performs better under 1% SLP and RLP. In this section an analysis is done to study the consequence of adding DSTS in a power system under random loading condition. The RLP is taken same as applied in the earlier section. The gains and other parameters of 2DOF-PID controller is optimized using WDO algorithm both in the presence and absence of DSTS. The dynamic responses so obtained with and without DSTS are compared and presented in Figure. 7. The responses clearly justify that in the presence of DSTS, the number and magnitudes of oscillations occurring in the system is less, and also dynamics settle faster. Hence, it can be concluded that DSTS can withstand the system fluctuations, whether it is in step, or random, in a better way if incorporated into the system.
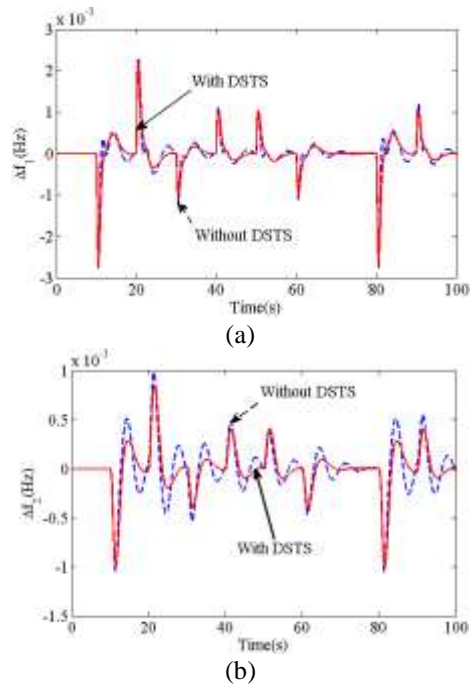
(a)

(b)

Figure 7. Comparison of dynamic responses with and without DSTS
under RLP (a) Δf_1-t and (b) Δf_2-t

C. Impact assessment of integrating Electric Vehicle in power system under 1% SLP

Electric vehicle is a form of energy storage device which stores electrical energy in the form of direct current, which can be integrated to grid for serving loads. The system taken for investigation consists of EV fleets connected in all the three areas. In this section, a study is carried out to evaluate the impact of incorporating EV in the system by comparing the dynamic responses in the absence of EV with those obtained in presence of EV in the power system under consideration. The comparison of the responses are shown in Figure. 8, from which it can be clearly seen that the responses obtained in presence of EV have lesser settling time, lower magnitudes and less number of oscillations. Hence, it can be concluded that the incorporation of EV in power system will help in enhancing the system dynamics.
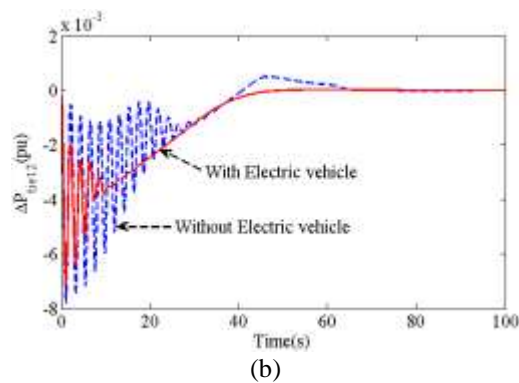

(a)

(b)
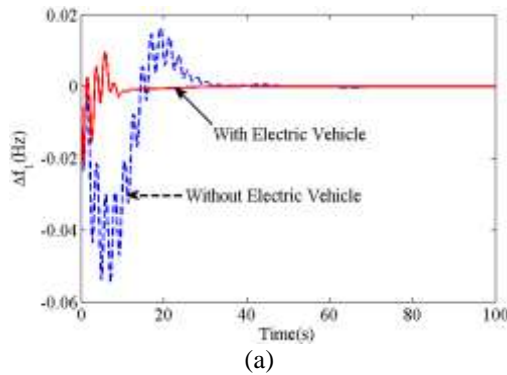
Figure 8. Comparison of dynamic responses with and without EV under 1% SLP, (a) Δf_1-t, and (b) ΔP_{tie12}-t

5. Conclusions

This paper presents an aggregate model of a three area system with a thermal system, Dish-Stirling solar thermal system (DSTS) and an Electric vehicle (EV) fleet in Area-1, a thermal plant and EV fleet in Area-2 and a thermal generating unit and EV fleet in Area-3 as well. The application of Two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controller is attempted in this work. Wind Driven Optimization technique is utilized for simultaneous optimization of the controller gains and parameters of the secondary controller used in all the three control areas. The dynamic responses obtained by 2DOF-PID controller is compared with those obtained using Proportional-Integral-Derivative (PID) controller, which reveals the superior performance of the former under both nominal 1% step load perturbation (SLP) and random load perturbation (RLP). The main contribution of this work lies in the incorporation of both EVs and DSTS with conventional thermal system. The importance of involving DSTS and EVs with the conventional system has been studied through comparisons of responses with and without DSTS, and with and without EVs under both 1% SLP and RLP. The results so obtained prove that with the incorporation of DSTS and EVs, the system dynamics have smoother curves in terms of settling time, number of oscillations and magnitude of fluctuations under load uncertainties.

6. References

[1]. O.I. Elgard, "Electric energy systems theory", (McGraw Hill, New York, 1982), pp. 299-362.

[2]. O.I. Elgerd, C. Fosha, "Optimum megawatt frequency control of multi-area electric energy systems", *IEEE Trans. Power Appl. Syst.*, Vol. PAS-89, No. 4, pp. 556-563, 1970.

[3]. P. Kundur, "Power system stability and control", (McGraw Hill, New York, 1994).

[4]. R.J. Abraham, D. Das, A. Patra, "Damping oscillations in tie power and area frequencies in a thermal power system with SMES-TCPS combination", *J Electr Syst*, Vol. 7, No. 1, pp. 71–80, 2011.

[5]. K.C. Divya, P.S. N. Rao, "A simulation model for AGC studies of hydro–hydro systems", *Int. J. Elec. Power and Energy Syst.*, Vol. 27, pp. 335–342, 2005.

[6]. B. Mohanty, S. Panda, P.K. Hota, "Controller parameters tuning of differential evolution algorithm and its application to load frequency control of multi-source power system", *Int. J. Elec. Power and Energy Syst.*, Vol. 54, pp. 77–85, 2014.

[7]. K.P.S. Parmar, S. Majhi, D.P. Kothari, "Load frequency control of a realistic power system with multi-source power generation", *Int. J. Elec. Power and Energy Syst.*, Vol. 42, pp. 426–33, 2012.

[8]. M. Abbas, B. Boumeddane, N. Said, "Dish Stirling technology: A 100 MW solar power plant using hydrogen for Algeria", *Int. J. Hydrog. Energy*, Vol. 36, pp. 4305–4314, 2011.

[9]. D.S. Martin, J.A. Martinez, J.E. Garcia, "Solar dish Stirling system optimisation with a doubly fed induction generator", *IET Renew. Power Gener.*, Vol. 6, No. 4, pp. 276–288, 2012.

[10]. B. Kongtragool, S. Wongwises, "A review of solar-powered Stirling engines and low temperature differential Stirling engines", *Renew Sustain Energy Rev*, Vol. 7, pp. 131–54, 2003.

[11]. J.R. Pillai, B. Bak-Jensen, "Integration of Vehicle-to-Grid in the Western Danish Power System", *IEEE Trans. Sustainable Energy*, Vol. 2, No. 1, pp. 12-19, 2011.

[12]. Thanh Ngoc Pham, Hieu Trinh, Le Van Hien, "Load Frequency Control of Power Systems with Electric Vehicles and Diverse Transmission Links Using Distributed Functional Observers", *IEEE Trans. Smart Grid*, Vol. 7, No. 1, pp. 238-252, 2016.

[13]. Yunfei Mu, Jianzhong Wu, Janaka Ekanayake, Nick Jenkins, Hongjie Jia, "Primary Frequency Response from Electric Vehicles in the Great Britain Power System", *IEEE Trans. Smart Grid*, Vol. 4, No. 2, pp. 1142-1150, 2013.

[14]. Seyedmahdi Izadkhast, Pablo Garcia-Gonzalez, Pablo Frías, "An Aggregate Model of Plug-In Electric Vehicles for Primary Frequency Control", *IEEE Trans. Power Systems*, Vol. 30, No. 3, pp. 1475-1482, 2015.

[15]. J. Nanda, A. Mangla, S. Suri, "Some findings on automatic generation control of an interconnected hydrothermal system with conventional controllers", *IEEE Trans. Energy Convers.*, Vol. 21, No. 1, pp. 187-193, 2006.

[16]. J. Sáncheza, A. Visioli, S. Dormido, "A two-degree-of-freedom PI controller based on events", *J Process Control*, Vol. 21, pp. 639–651, 2011.

[17]. R.K. Sahu, S. Panda, U.K. Rout, "DE optimized parallel 2-DOF PID controller for load frequency control of power system with governor dead-band nonlinearity", *Int. J. Elec. Power and Energy Syst.*, Vol. 49, pp. 19–33, 2013.

[18]. S. Pothiya, I. Ngamroo, "Optimal fuzzy logic-based PID controller for load– frequency control including superconducting magnetic energy storage units", *Energy Convers Manage.*, Vol. 49, pp. 2833–2838, 2008.

[19]. D.K. Chaturvedi, P.S. Satsangi, P.K. Kalra, "Load frequency control: a generalized neural network approach", *Int. J. Elec. Power and Energy Syst.*, vol. 21, pp. 405–15, 1999.

[20]. H. Gozde, M.C. Taplamacioglu, I. Kocaarslan, "Comparative performance analysis of Artificial Bee Colony algorithm in automatic generation control for interconnected reheat thermal power system", *Int. J. Elec. Power and Energy Syst.*, Vol. 42, pp. 167–78, 2012.

[21]. S.P. Ghosal, "Optimization of PID gains by particle swarm optimization in fuzzy based automatic generation control", *Electr Power Syst Res*. Vol. 72, No. 3, pp. 203–12, 2004.

[22]. R.K. Sahu, S. Panda, P. C. Pradhan, "Design and analysis of hybrid firefly algorithm-pattern search based fuzzy PID controller for LFC of multi area power systems", *Int. J. Elec. Power and Energy Syst.*, Vol. 69, pp. 200–212, 2015.

[23]. S. Panda, N.K. Yegireddy, "Automatic generation control of multi-area power system using multi-objective non-dominated sorting genetic algorithm-II", *Int. J. Elec. Power and Energy Syst.*, Vol. 53, pp. 54–63, 2013.

[24]. Ali, S. Abd-Elazim, "Bacteria foraging optimization algorithm based load frequency controller for interconnected power system", *Int. J. Elec. Power and Energy Syst.*, Vol. 33, pp. 633–638, 2011.

[25]. Z. Bayraktar, M. Komurcu, A.J. Bossard, D.H. Werner, "The Wind Driven Optimization Technique and its Application in Electromagnetics", *IEEE Trans. Antennas and Propagation*, Vol. 61, No. 5, pp. 2745-2757, 2013.

Appendix

Nominal parameters of the systems	Values
f	60 Hz
T_g	0.08s
T_t	0.3s
T_r	10s
K_r	0.5
K_{ps}	120 Hz/pu MW
T_{ps}	0.08s
$T_{12=}\ T_{23=}\ T_{31}$	0.086 pu MW/rad
H_i	5s
D_i	8.33x10-3pu MW/Hz
$B_i = \beta_i$	0.425 pu MW/Hz
R_i	2.4 pu Hz/MW
nominal loading	50%
R_{EV}	2.4 pu Hz/MW
K_{EV}	1
T_{EV}	1s
K_{DSTS}	1
T_{DSTS}	5s

Pushpa Gaur received the B. E. Degree in electrical engineering from Assam Engineering College, Guwahati, Assam, India, in 2011 and M. E. Degree in power system engineering from Assam Engineering College, Guwahati, Assam, India, in 2014. She is pursuing Ph.D. in the Electrical Engineering Department, National Institute of Technology, Silchar, Assam, India. Her research interests include power system operation and control, renewable energy, load frequency control and power system planning. She has worked as Assistant Professor in the Department of Electrical Engineering, Girijananda Institute of Management and Technology, Guwahati.

Nirmala Soren (M'09) has completed Bachelor Degree B.Sc (Engineering) from Electrical from RIT (now NIT), Jamshedpur, Jharkhand, India and M.Tech. Degree (Energy Management) from SEES, DAVV, Indore, India in 2007. She has been awarded Ph.D. Degree from School of Electrical Engineering, KIIT University, Bhubaneshwar, Odhisa, India in Dec. 2011. Her research interests include Renewable Energy Sources such as Wind, Solar; biomass, etc., Electric Power and Energy Systems; Rural Energy Planning, Solid Waste Management System, Distributed Generation Systems, Demand Side Management. Presently, she is working as an Assistant Professor in Electrical Engineering Department, NIT Silchar, Assam, India since 31st October, 2014.

Debashish Bhowmik received his B. Tech. Degree in electrical engineering from the National Institute of Technology, Agartala, Tripura, India, in 2011 and M. Tech. Degree in power system engineering from the National Institute of Technology, Agartala, Tripura, India, in 2013. He has completed his Ph.D. from the Department of Electrical Engineering, National Institute of Technology, Silchar, Assam, India, in June 2018. His current research interests include power system planning, power system control, power system economics, power flow resolution, renewable energy, load frequency control, power flow tracing and phasor measurement unit (PMU). He worked as an Assistant Professor with the Electrical Engineering Department, Royal Group of Institutions, Guwahati. Presently, he is working as an Assistant Professor with the Electrical Engineering Department, Tripura Institute of Technology, Narsingarh, Agartala, Tripura, India.