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Research paper

Impact Assessment of Vehicle-to Grid in Frequency Control of Multi-area Hybrid System

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Abstract

Vehicle-to-grid (V2G) may play a vital role in the frequency regulation of an interconnected power system in the near future. This paper presents a frequency regulation scheme of a multi-source power system with the integration of renewable energy source (RES) and electric vehicles (EVs). The application of Two Degree of Freedom Proportional-Integral-Derivative (2DOF-PID) controller and a new optimization technique called as Wind Driven Optimization for simultaneous optimization of the controller gains and parameters has been attempted. Comparison of 2DOF-PID controller with classical controllers like Proportional-Integral-Derivative, Proportional-Integral, and Integral controllers reveals the superiority of the former under nominal as well as random system conditions. The impact of addition of RES and EVs into the system is verified in terms of reduction of the magnitude and numbers of oscillations of the system responses under nominal. The system may encounter simultaneous change in loading in more than one areas. Hence, the effectiveness of EVs has been tested under simultaneous perturbation in two and three areas, and the performance of V2G is appreciable under simultaneous perturbation also.

Keywords: *Classical controllers; Frequency regulation; Multi-source systems; Renewable energy sources; Vehicle-to-grid.*

1. Introduction

There has been a tremendous increase in electric power consumption which has forced the electrical power generation utilities to generate more power. The balance between demand and supply must be maintained for smooth functioning of the power system. For efficient functioning of power system, it is highly essential to sustain constant frequency constant tie line power flow [1]. This is the job of load frequency control (LFC) to maintain this balance in the system by minimizing the area control errors.

In the race of meeting the growing demand of electrical power, the pollution has increased at an alarming rate that is caused by the thermal power plants. Hence, the researchers are now trying to utilize non-conventional sources of power generation. In recent years, extraction of electrical power from solar power has steeply increased. Battery energy storage system (BESS) plays an important role in maintaining the system frequency deviation by providing the stored energy to the grid. One such highly recommended BESS nowadays is the implementation of vehicle-to-grid (V2G) based on the concept of controlling the charging and discharging between the vehicle and the power system.

Literature survey reveals the idea of modelling of integrated two area thermal power system was given by Elgard and Fosha [2]. This idea has been carried forward by many researchers. In [3] the authors studied LFC of a hydro thermal system with the use of conventional controllers like Integral and Proportional-Integral controllers, with the utilization of mechanical governors in the thermal units. Most of the LFC studies have been done for thermal and hydrothermal systems, and not much have been done in gas thermal power plants. Many researchers are now working in LFC of multi area multi-source involving different types of scenarios, one of which is deregulation [4]. Literature shows that researchers nowadays are moving towards application of renewable energy sources like solar, wind, etc. Modelling of solar thermal power generation of parabolic trough collector type has been attempted in [5]. With the growing emphasis of BESS, and V2G technologies, which is also one kind of BESS, many studies are being carried out to evaluate the impact of its integration with the conventional power system [6-10].

For stabilizing deviations in tie power and system frequency, different types of controllers have been employed by various researchers. Classical controllers like Proportional-Integral-Derivative, Proportional-Integral and Integral controllers were used by a number of researchers. But with the increasing complexity in power systems, there is a necessity to explore other controllers, like two Degree of Proportional-Integral-Derivative (2DOF-PID) [11]. Several artificial intelligent controllers like fuzzy controllers, neural network controllers have also been employed by few [12, 13], but these controllers are very slow in operation. 2DOF-PID has many ad-vantages over other controllers discussed above, but its utilization is very limited, and hence provides scope for further utilization.

A number of optimization techniques have been used for optimization the gains of the controllers utilized for secondary frequency regulation. Classical techniques based on trial and error techniques were extensively used in AGC in many literatures. In the later stages in AGC of multi-area system where number of parameters to be optimized are more, various heuristic algorithms have been used for optimization. Heuristic techniques such as genetic algorithm (GA) [14], particle swarm optimization (PSO) [15], bacteria foraging (BFO) [16], artificial bee colony algorithm (ABC) [17], firefly algorithm (FA) [18], etc. have been applied in AGC for simultaneous optimization of number of parameters of controllers. An optimization technique inspired by nature called as Wind Driven Optimization has been utilized by Bayraktar et al. [19] in electromagnets and WDM channel allocation algorithm respectively. Its utility is yet to be tested for LFC of multi area system. Hence, this provides a new scope for further investigation.

After carrying out an extensive literature survey, it has been found out that LFC of multi-source system with RES and EV is still not widely explored. Also the application of 2DOF-PID controller is very limited in LFC studies, hence, this provides further scope for investigation. Moreover, WDO technique has not found application in LFC, so, this can be further studied. In view of the survey done above the main objectives of this work are:

1) To Model of a three area multi-source power system with solar-thermal power plant and electric vehicles (EVs)
2) To apply 2DOF-PID controller and compare its performance with other classical controllers like PID, PI, and I to estimate the best controller.
3) To use Wind Driven Optimization technique for optimizing the gains and parameters of the controllers.
4) Impact assessment of including RES and EVs in the system.

2. Modelling of multi-area power system

The system is designed with a RES unit and a thermal unit with single reheat turbine in Area-1. Area-2 consists of a gas unit, a thermal unit with single reheat turbine and an electric vehicle (EV) fleet embedded as the third unit. Similarly, Area-3 consists of two thermal units with single reheat turbine and an EV fleet. Appropriate generation rate constraints of 3% per minute and 20% per minute are taken for thermal and gas units, respectively. The generating capacities of the units in the interconnected system are in the ratio Area-1:Area-2:Area-3=1:3:5. The transfer function model for the system under investigation is given in Fig.1.
The parameters for the other units have been given in Appendix. Every unit consists of speed governing system, turbine and gene-ra-tor. The area control error (ACE) of each area is given by (1):

$$ACE = B\Delta f + \Delta P_{tie} \tag{1}$$

Where, B is frequency bias.
The control centres receives control signals in terms of power set point so as to regulate the power outputs of the generating units and EVs. The EVs insert electrical power into the grid and the capacity of power can contribute to frequency control of a power system. The details on EVs are provided to the control centres with the aid of aggregators. The model of a vehicle-to grid is shown in Fig. 2.

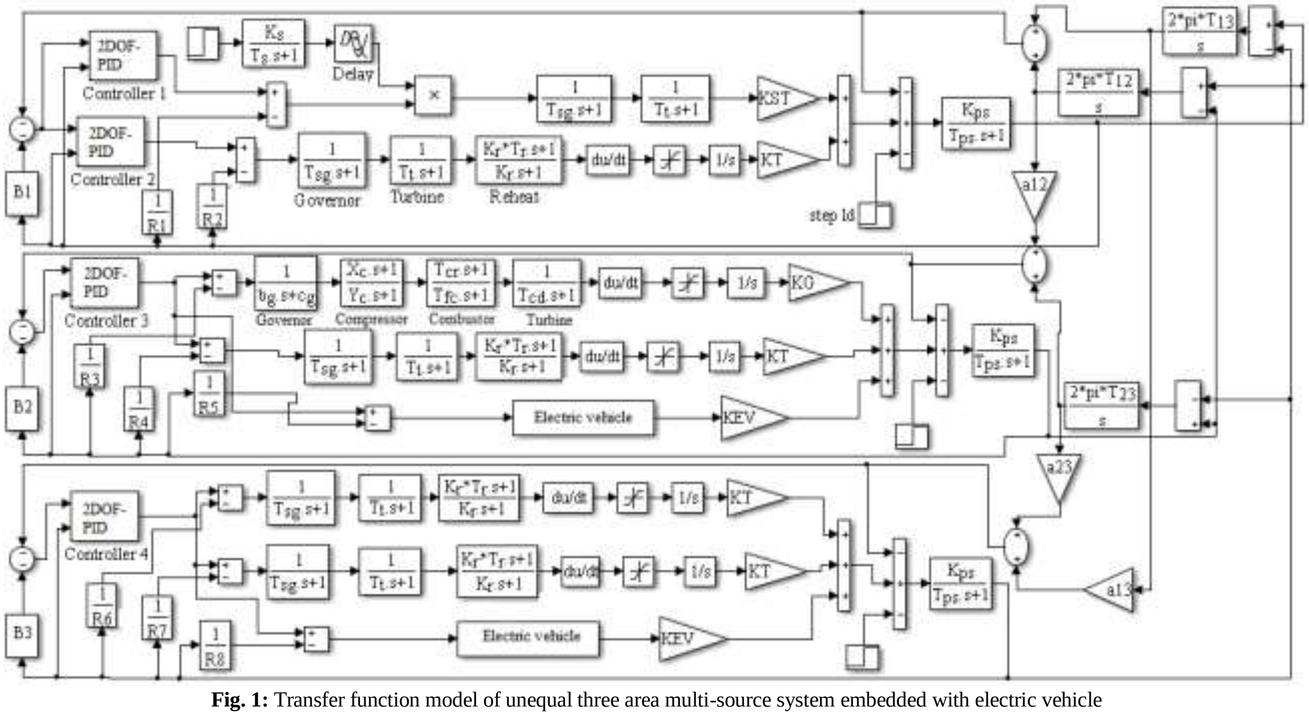


Fig. 1: Transfer function model of unequal three area multi-source system embedded with electric vehicle

The transfer function of an aggregate EV fleet is given by (2):

$$TF_{EV} = \frac{K_{EV}}{1 + sT_{EV}} \tag{2}$$

Where, K_{EV}=1 is the gain of EV, and T_{EV}=1 is the time constant of the battery for EV.
Solar energy has the capacity of meeting the increasing power demand. There are various ways of trapping solar energy, one of which is parabolic trough collector. The transfer function model for parabolic trough collector type is given by equation (3):

$$TF_{Solar} = \frac{K_s}{T_s.s + 1} \tag{3}$$

The objective function considered for the multi-area multi source power system is integral square error and is represented by equation (4):

$$J = \int_0^T \left\{ \left(\Delta f_i\right)^2 + \left(\Delta P_{tiej-k}\right)^2 \right\} dt \tag{4}$$

Where, Δfi is the frequency deviation in Area-1 and ΔP_{tiej-k} is the deviation in tie line power in tie connecting area j and k.

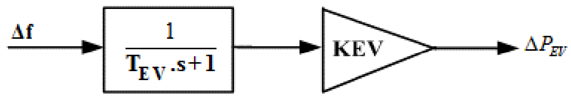


Fig. 2: Transfer function model of vehicle-to-grid

3. Two degree of freedom proportional-integral-derivative controller

The degree of freedom is the number of closed loop transfer functions that is responsible to be adjusted autonomously. The schematic diagram of two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controller is shown in Fig. 3.
R(s), Y(s) and U(s) are the reference signal, feedback from the measured system output, and output signal respectively. Proportional, integral and derivative gains are represented respectively by K_p, K_i and K_d. PSW set point weights of proportional and DSW is the set point weights of derivative.
It is important to select a suitable objective function based on optimization technique for designing a controller. There are various objective functions available in literature, but Integral of Squared Error (ISE) performs better. Hence, in this work, ISE has been applied as objective function which is given by equation (4).

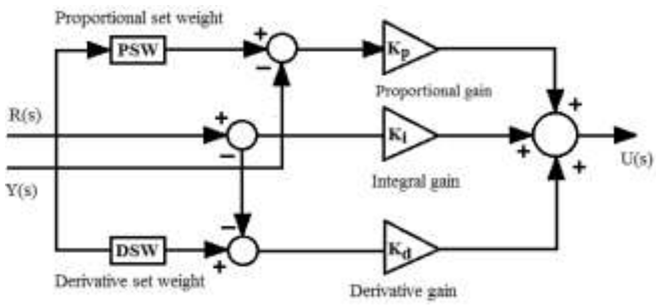


Fig. 3: Schematic diagram of 2DOF-PID Controller

4. Wind Driven Optimization Technique

An algorithm inspired by nature called Wind Driven Optimization (WDO) has been proposed by the author in [19]. The wind usually 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. This idea is taken for designing this algorithm. Vertical movement is assumed to be weaker than the horizontal movement, hence, the change in pressure as well as the motion of wind can be taken as a horizontal movement. The algorithm starts with Newton's second law of motion given by equation (5):

$$\rho a = \sum F_i \quad (5)$$

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

$$P = \rho RT \quad (6)$$

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, the friction force (FF), gravitational force (FG), Coriolis force (FC) and pressure gradient force (FPG) which is the most dominant force that helps in the movement of air. 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, gravitational acceleration is denoted by g, and velocity vector of the wind is denoted by u.

$$F_F = \rho \alpha u \quad (7)$$

$$F_G = \rho \delta V_g \quad (8)$$

$$F_C = -2\Omega * u \quad (9)$$

$$F_{PG} = -\nabla P \delta V \quad (10)$$

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 by equation (11):

$$\rho \Delta u = \left(\rho \delta V_g\right) + \left(-\nabla P \delta V\right) + \left(-\rho \alpha u\right) + \left(-2\Omega * u\right) \quad (11)$$

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 and an assumption of time step to be unity (Δt = 1) is taken which gives the velocity update equation given by (12):

$$u_{new} = \left(1-\alpha\right) u_{cur} - g x_{cur} + \left(\frac{c u_{cur}^{otherdim}}{P_{cur}}\right) + \left(\frac{RT}{P_{cur}} \mid P_{opt} - P_{cur} \mid \left(x_{opt} - x_{cur}\right)\right) \quad (12)$$

The updating of the location of air parcels and their velocity is done in each iteration using equation (12), whereas, updating their position is done by employing equation (13):

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

Algorithm applied in this paper is shown below:
Steps:
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

If the maximum number of iterations is reached, then stop, otherwise go to step 3.

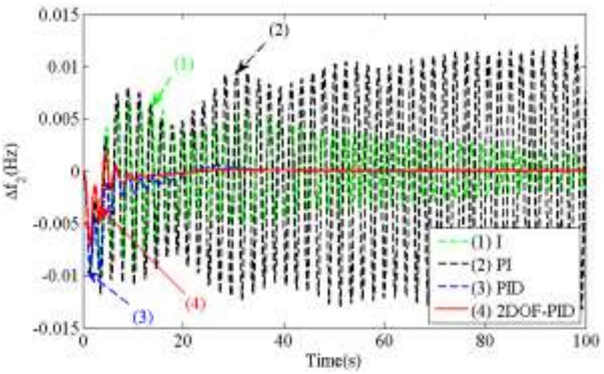
5. Simulation results

A three area system with the inclusion of electric vehicles (EVs) and RES is taken into consideration for the study of load frequency control (LFC). The study is carried out under nominal system conditions of 1% step load perturbation (SLP), 50% loading and inertia constant (H) as 5s. Wind driven Optimized two degree of freedom Proportional-Integral-derivative (2DOF-PID) controller is used for analysis. A number of studies have been carried out which are explained below.

5.1. Dynamic response comparison of 2DOF-PID, PID, PI and I controllers with 1% SLP in Area-1

The performance of 2DOF-PID controller has been compared with other classical controllers like Proportional-Integral-Derivative (PID), Proportional-Integral (PI) and Integral (I) controllers under nominal system conditions. The optimized values of gains of

2DOF-PID, PID, PI and I controllers are presented in Table I. the gains of the controllers are optimized by using WDO technique and the responses so obtained have been compared and shown in Fig. 4. The values of peak overshoot and undershoot and settling time are noted in Table II. It is evident from Table II and the responses in Fig. 4 that 2DOF-PID is superior to other classical controllers under the nominal system conditions.



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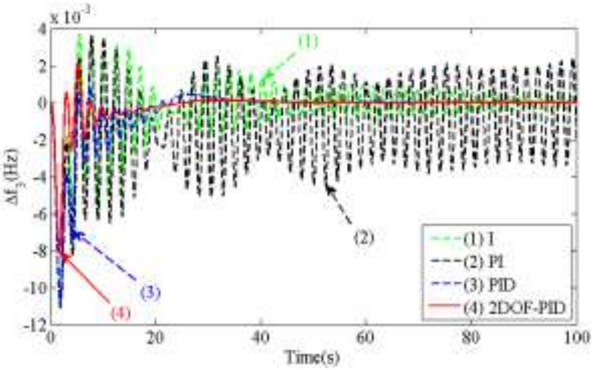


(b)

Fig. 4: Comparison of responses of 2DOF-PID, PID, PI, and I controllers
(a) Δf_2 vs time
(b) Δf_3 vs. time

Table 1: Optimum values of gains of secondary controller

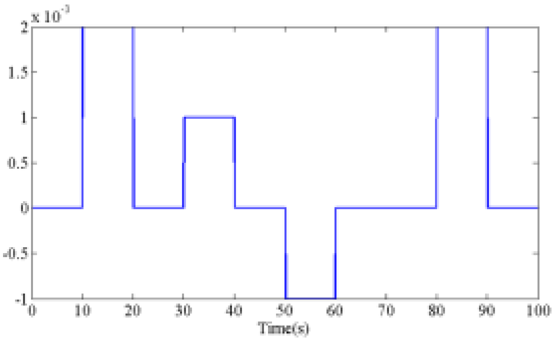
Controller	Gains	Optimum values			
		Controller 1	Controller 2	Controller 3	Controller 4
2DOF-PID	K_{Pi}^*	0.6970868	0.9974926	0.6405529	0.3732591
	K_{Ii}^*	0.6501835	0.2808193	0.0835044	0.6372138
	K_{Di}^*	0.4842358	0.4437443	0.1126157	0.2769131
	b_i^*	0.1922451	0.2221732	0.0172703	0.3348981
	c_i^*	0.9959599	0.1098072	0.6638417	0.8609594
PID	K_{Pi}^*	0.2508786	0.7748541	0.2445226	0.2671636
	K_{Ii}^*	0.8613481	0.9545478	0.4051104	0.7949918
	K_{Di}^*	0.9869720	0.3247121	0.4194977	0.3194943
PI	K_{Pi}^*	0.3394934	0.1711210	0.5829863	0.1787661
	K_{Ii}^*	0.6109586	0.0679927	0.0357627	0.6444427
I	K_{Ii}^*	0.3279379	0.6658251	0.4670191	0.5495286

Table 2: Values of settling time, peak overshoot and peak undershoot for Fig. 4

	Controller	Fig. 4(a)	Fig. 4(b)
Settling time (s)	2DOF-PID	33.57	28.67
	PID	39.24	41.9
	PI	NS	NS
	I	NS	NS
Peak over-shoot	2DOF-PID	0.001711	0.002122
	PID	0.0004895	0.0008943
	PI	-	-
	I	-	-
Peak under-shoot	2DOF-PID	0.007039	0.007991
	PID	0.009346	0.01088
	PI	-	-
	I	-	-

5.2. Dynamic response comparison of 2DOF-PID and PID controllers with random load in Area-1

It is observed from the previous section that the performance of PI and I controller is very poor, hence, for the further analysis, PI and I controllers will not be used, only 2DOF-PID and PID controllers will be utilized. In this section, an investigation is carried out to estimate the best controller under random loading conditions. For this, the SLP in Area-1 is replaced by a random load perturbation (RLP) as shown in Fig. 5(a). The 2DOF-PID and PID controllers are set at the optimum values shown in Table I, SLP is replaced by RLP, and the simulation is run. The responses attained by both the controllers are compared and shown in Fig. 5(b) and 5(c). It can be concluded from the comparison that 2DOF-PID controller outperforms PID controller RLP as well. Hence, for the system considered, 2DOF-PID controller proves to be the best controller under the given system conditions.



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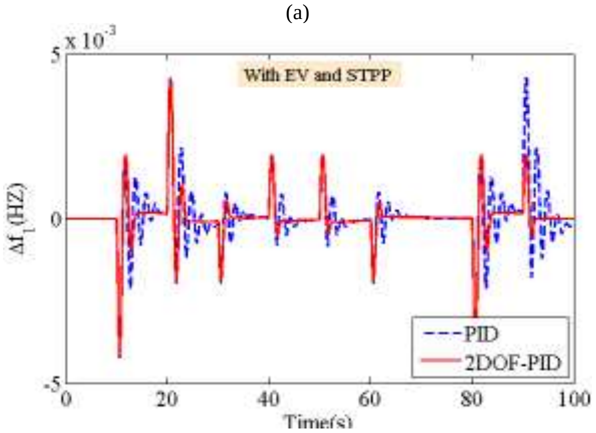

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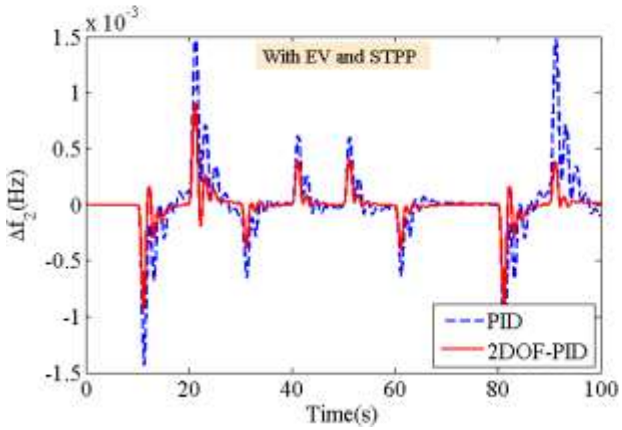
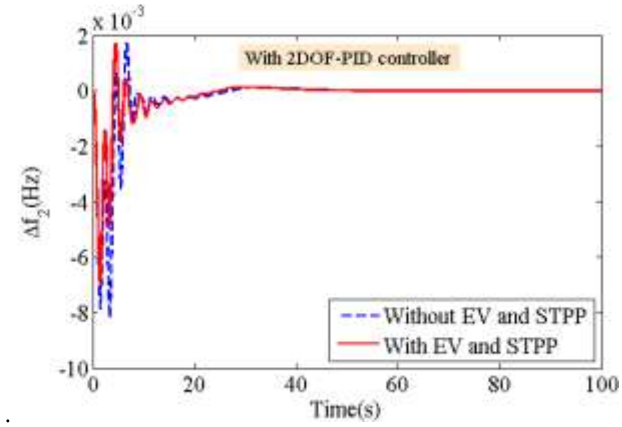


(c)

Fig. 5: (a) Applied RLP (b) Δf_1 vs. time (c) Δf_2 vs. time

5.3. Impact valuation of incorporating RES and EV in the power system

In conventional power system, thermal and hydrothermal were used for generating electric power. But this gives rise to environmental hazards due to the harmful emissions. Hence, the researchers are shifting to other sources of power generation which are eco-friendly nature, like RES and V2G. In this section, a study is done to evaluate the impact of introducing RES and EV in the system for meeting the increasing load demands under nominal system condition. The previous sections reveal that 2DOF-PID controller is the best controller for this system, hence, only this controller is used for further studies. The dynamic responses are obtained with the gains of 2DOF-PID controller set at the values shown in Table 1. The system is tested with EV and RES (which in this paper is solar thermal power plant (STPP)), and without EV and STPP. The responses in both the cases are obtained, compared and shown in Fig. 6. The comparison reveals that in the presence of EV and STPP, the responses are smoother with less magnitudes of oscillations.



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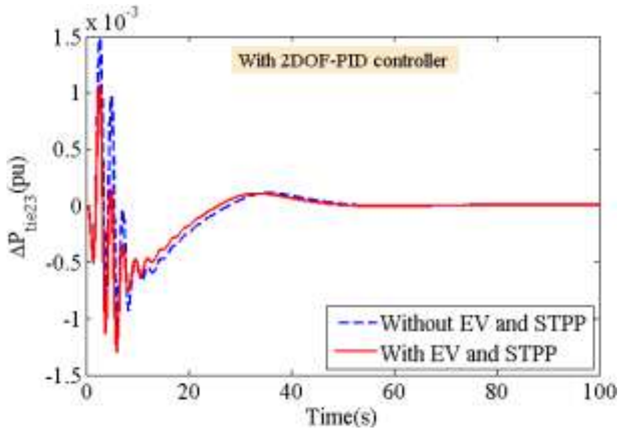
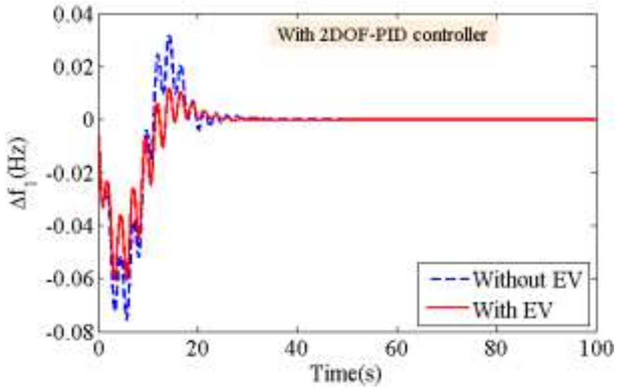


(b)

Fig. 6: Comparison of responses in the presence and absence of EVs and STPP
(a) Δf_2 vs time
(b) ΔP_{tie23} vs. time

In the studies carried out above, the impact of including EV in the system is tested under nominal system conditions. There is also a necessity to verify the effectiveness of EV integration with conventional power system under simultaneous perturbation in two areas and in three areas for frequency regulation. Hence, an analysis has been carried by comparing the system responses obtained in the absence of EVs with those in presence of EVs firstly with simultaneous perturbation in two areas, then in three areas.

The comparisons is shown in Fig. 7, reveal the effectiveness of EVs in regulating system frequency even under simultaneous perturbation in two or more areas of the power system.



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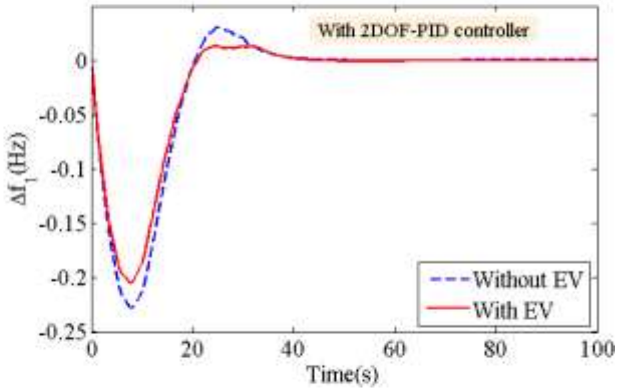

(b)

Fig. 7: Comparison of responses in the presence and absence of EVs
(a) Δf_1 vs time with simultaneous perturbation in two areas
(b) Δf_1 vs. time with simultaneous perturbation in all the areas

6. Conclusion

This paper presents an aggregate model of a multi-source system with the incorporation of vehicle-to-grid (V2G) and solar thermal power plant (STTP). The application of Wind Driven Optimized two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controller has been made. The performance comparison of 2DOF-PID and Proportional-Integral-Derivative (PID) controller reveals the superior performance of the former under both nominal system condition and random loading condition. Analysis also reveals that the integration of V2G and STPP enhances the system dynamics. Also, the integration of EVs in the system can also handle fluctuations well even when the system encounters simultaneous perturbation in two or more areas. Hence, the traditional power systems can be made to integrate with V2G and renewable energy sources in the near future for minimizing the environmental pollution

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Appendix

Appendix A: Nomenclature

f	nominal frequency of system (Hz),
*	represents optimum value,
i	subscript referred to area i (1, 2, 3),
T_{sgi}	Steam governor’s time constant (s),
T_{ti}	Turbine’s time constant (s),
K_{ri}	Reheat coefficient of steam turbine,
T_{ri}	Reheat time constant of Steam turbine (s),
K_s	Gain of solar field,
T_s	Time constant of solar field (s),
T_{cdi}	Gas turbine compressor discharge volume-time constant (s),
X_{ci}	Gas turbine speed governor lead time constant of (s),
Y_{ci}	Gas turbine speed governor lag time constant of (s),
c_{gi}	Valve positioner of gas turbine,
b_{gi}	Valve positioner gas turbine constant of (s),
T_{fci}	Time constant of gas turbine fuel (s),
T_{cri}	Time delay of gas turbine combustion reaction (s),
H_i	Inertia constant of area i (s),
R_i	Speed regulation parameter of governor of area i,
B_i	frequency bias constant of area I,
K_T	Participation factor of thermal unit,
K_{EV}	Gain of electric vehicle unit,
K_G	Participation factor of gas unit.

Appendix B: Nominal values

Nominal parameters of the systems	Values
f	60 Hz
T_{sgi}	0.08s
T_{ti}	0.3s
T_{ri}	10s
K_{ri}	0.5
K_{pi}	120 Hz/pu MW
T_{pi}	0.08s
b_g	0.5
c_g	1
X_c	0.6 s
Y_c	1 s
T_{cr}	0.01 s
T_{fc}	0.23s
T_{cd}	0.2 s
$T_{12=}\ T_{23=}\ T_{31}$	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
K_s	1.8
T_s	1.8s
nominal loading	50%