Secondary Frequency Control of a Multi-area Power System Integrated with Plug-in Electric Vehicles and Renewable Energy Sources

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***Abstract* - The integration of plug-in electric vehicles (PEVs) has a number of benefits, due to which the number of PEVs integration to the power system is likely to rise. One major benefit of PEVs integration is their contribution in the frequency regulation of the system under load fluctuations. This paper presents an aggregate model of a power system with the integration of renewable energy sources (RES) and PEVs. For the purpose of secondary frequency control, Wind Driven Optimized two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controller is applied. The impact of integrating RES and PEVs to the multi-area interconnected power system has been studied vigorously under nominal system conditions in this paper. It is found out from the studies that PEVs play a very vital role in frequency regulation. Also, the effect of PEVs and RES has been studied under random loading conditions, and it is revealed that the impact is very effective.**

Keywords - Frequency regulation; Plug-in electric vehicles; Renewable energy sources; Two degree of freedom Proportional-Integral-Derivative controller; Wind Driven Optimization.

I. Introduction

The power system is a combination of generation, transmission and distribution of electrical power to the consumers. It is very necessary for the power producers to maintain a balance between electrical power demand and supply. Any deviation in this balance may lead to deviation in system frequency and tie line power interchange between the interconnected areas. Load frequency control plays a vital role in maintaining this balance of demand and supply. But, in this race of supply following the demand, a very huge exploitation of fossil fuels is required for generation of power. This leads to more consumption of fossil fuels which risk their availability in the near future. Also, the burning of fossil fuels results in environmental pollution which is increasing at an alarming rate. In order to minimize this environmental hazard, the researchers are focusing on some alternative sources of electrical power generation. Many non-conventional energy sources of power generation like solar, wind, tidal, geothermal, etc. has been successfully adopted for generation of power. The researchers are also finding out many other modes of power generation, also, they are trying to store the generated power in the form of energy storage devices. Nowadays, the researchers are also planning to integrate the electric vehicles (EVs), which are in the idle condition, to the grid, so that, the electrical energy stored in the vehicle battery can feed power to the grid in the discharging mode.

Many researchers have worked in the area of load frequency control (LFC) for different systems like thermal, hydro-thermal, hydro-hydro system [1-3]. With the increasing demand of electrical power, and also searching for alternate eco-friendly sources of power generation, researchers have diverted towards renewable energy sources (RES) of power generation. One such source is solar power, the transfer function model for which is derived by the author in [4]. Also, the integration of EVs to conventional power system in form of battery energy storage system has been attempted by a number of researchers [5-9]. The authors have also integrated RES along with PEVs to the existing power system.

In LFC studies, a secondary controller is utilized for frequency regulation of the system under load fluctuations. Literature survey shows that there are various types of controllers used by several researchers for secondary frequency control like conventional controllers, Proportional-Integral-Derivative controller, two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controller, artificial intelligence based controllers, etc. [10-13]. The secondary controllers when used in power system has to be set at certain values of controller gains. These values can be chosen either on trial and error basis, or can be optimized by using optimization techniques. Many researchers have employed heuristic techniques such as genetic algorithm [14], particle swarm optimization [15], artificial bee colony algorithm [16], firefly algorithm [17], bacteria foraging [18] in LFC for optimizing the gains of controllers. An optimization technique inspired by nature called as Wind Driven Optimization has been utilized by Bayraktar et al. [19] in electromagnets.

Based on the extensive literature survey carried out, it has been observed that the application of PEVs along with solar power generation has not been integrated to conventional thermal power system. Also, the application of 2DOF-PID controller is not widely used in LFC studies in the past, which provides a further scope for study. Moreover, WDO technique shows excellent results in the area in which it has been applied, but still it lacks application in LFC studies. Hence, this provides further scope of study. On the basis of these, the objectives for this work are:

1. To design a three-area thermal system with integration of PEVs and STPP.
2. To apply WDO technique for simultaneous optimization of the gains of 2DOF-PID controller.
3. To find the best controller amongst 2DOF-PID and PID controller for the system designed under different system conditions.
4. To analyze the impact of incorporating PEVs and STPP to the conventional system under various system conditions.

II. METHODOLOGY

A. *System modelling*

The system considered for study in this work is a three area thermal system integrated with plug-in electric vehicles (PEVs) and solar-thermal power plant (STPP). Area-1 consists of a thermal power generating unit equipped with single reheat turbine and generation rate constraint (GRC) of 3% per minute, an STPP and PEVs. Area-2 and Area-3 comprise of thermal units with single reheat turbines and GRC of 3% per minute and PEVs. The control areas are provided with two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controllers, the gains and other parameters of which are optimized by using Wind Driven Optimization (WDO) technique. The transfer function model for the system is shown in Fig. 1. The nominal parameters of the system are given taken from [3] and [6]. The objective function considered for this study is given by:

$$J = \int_{0}^{T} \left\{ \left(\Delta f_i\right)^2 + \left(\Delta P_{tiej-k}\right)^2 \right\} dt \tag{1}$$

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

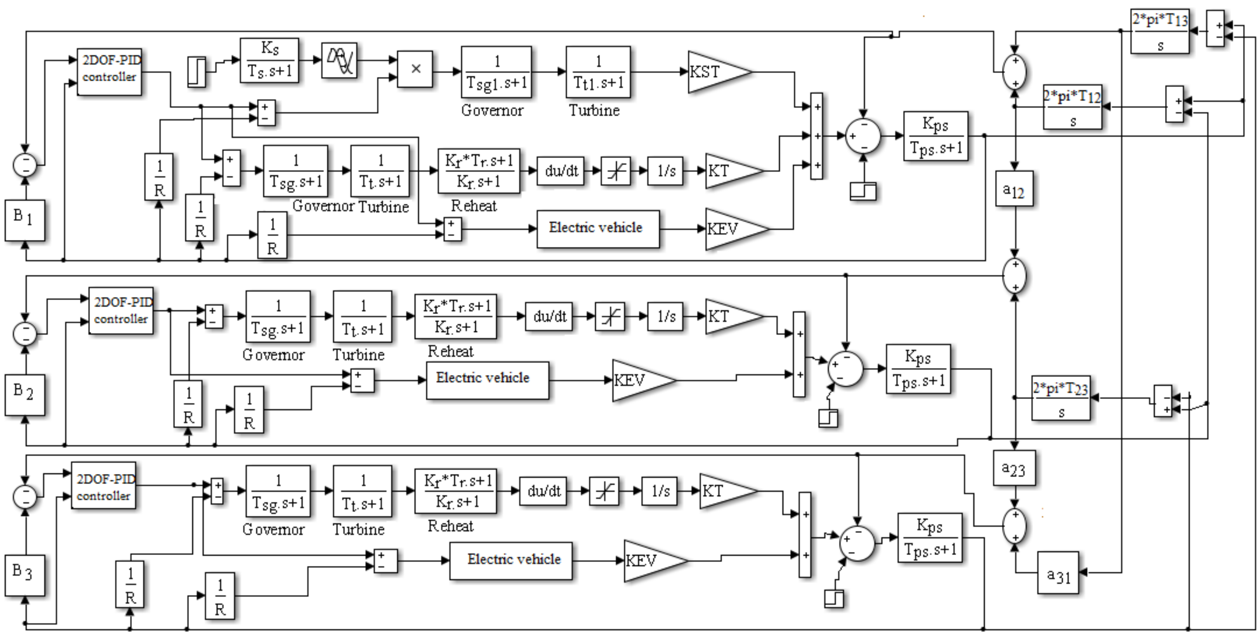


Fig. 1. Three area thermal system integrating STPP and PEVs

As discussed above, an STPP is placed in Area-1 as a generating unit. It is well known that solar energy is capable of meeting the increasing power demand. There are a number of technologies designed for harnessing energy from the sun. Photovoltaic system and concentrated solar power plant are two of them. Many studies have been done on the types of solar collector such as parabolic trough collector, dish-stirling, flat plate collector, etc. The main task of these collectors is to collect the solar energy and focus on the pipelines carrying fluids, so that it gets heated up and is used for the production of steam in the heat exchanger which further can be utilized to rotate the turbine blades. In this work, parabolic trough collector is considered, the transfer function model for parabolic trough collector type is given by equation (2):

$$TF_{Solar} = \frac{K_S}{T_S.s + 1} \tag{2}$$

Where, K_s is the gain of solar field which is taken to be 1.8, and T_s is the time constant of solar field which is taken to be 1.8 seconds.

The PEVs are capable of injecting electrical power into the grid during discharging, and the capacity of power can be contributed to load frequency control of a power system. The details on PEVs are collected with the help of aggregators and are provided to the control centers. The aggregator also receives information on power set point from the control centers and accordingly allocates to PEVs. The model of a PEVs is shown in Fig. 2.

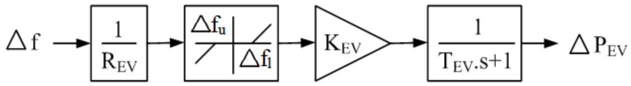


Fig. 2. Transfer function model of plug-in electric vehicles

The transfer function of an aggregate EV fleet is given by (3):

$$TF_{EV} = \frac{K_{EV}}{1 + sT_{EV}} \quad (3)$$

Where, K_{EV} is the gain of electric vehicle (EV) which is taken to be 1 for the EV fleet to participate in LFC, and T_{EV} is the time constant of the battery for EV. The value of T_{EV} is taken to be 1.

B. *Controller*

The secondary controller used in the presented work is a two degree of freedom Proportional-Integral-Derivative (2DOF-PID) controller each in all the three control areas. Degree of freedom is the number of closed loop transfer function which can be adjusted separately. The controller has two inputs and a single output system with set point variables named as proportional set point (b) and derivative set point (c). Proportional gain (K_p), integral gain (K_i), derivative gain (K_d), b and c are the five parameters which can be tuned in 2DOF-PID controller. The schematic diagram of 2DOF-PID controller with filter is shown in Fig. 3.

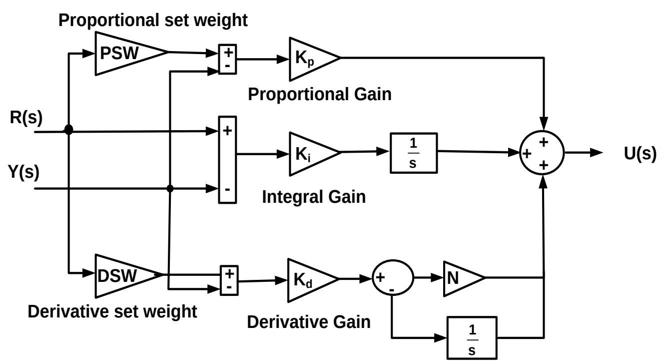


Fig. 3. Schematic diagram of Two Degree of Freedom Proportional-Integral-Derivative Controller

In a power system, fluctuations caused in the system due to change in load demand have to be settled to zero at the earliest. In Integral of Squared Error (ISE), the error is integrated over time due to which large errors can be removed quickly which results in fast response, hence, in this work ISE has been chosen as objective function.

C. *Optimizing technique*

The wind always flows from a higher pressure region to lower pressure region with a speed relative to the pressure gradient. This theory motivated the authors in [19] to develop a novel meta-heuristic algorithm called Wind Driven Optimization (WDO). Hydrostatic air balance and that vertical movement is weaker than horizontal movements are assumed, and hence change in air pressure as well as motion of wind can be taken to be horizontal movement. Although, our world is three-dimensional, the motion of wind addresses multi-dimensional problems. More assumptions and simplifications are required for deriving the operators employed in WDO algorithm. The algorithm involves Newton's law of motion. It also considers a number of forces which affects the motion of wind.

The steps initiate from initialization of parameters and end at checking Golombness and ranking the population from best to worst. The different parameters of WDO technique [19] are population size = 50, maximum number of iteration = 500, RT coefficient = 3, Coriolis effect = 0.4, maximum allowed speed = 0.3.

III. RESULTS AND DISCUSSIONS

The system under consideration is a three area thermal system incorporated with RES and PEVs. WDO technique is used for optimization of the gains and parameters of 2DOF-PID controller. A number of analyses have been done which are given below.

A. *Under nominal condition*

This section discusses about the analyses carried out under nominal system condition of 1% step load perturbation (SLP) in Area-1, 50% nominal loading and inertia constant (H) of 5 seconds. The performance of WDO optimized 2DOF-PID controller is compared with WDO optimized classical proportional-Integral-Derivative (PID) controller to find the best controller amongst the two. The optimized values of the controller gains are given in Table I.

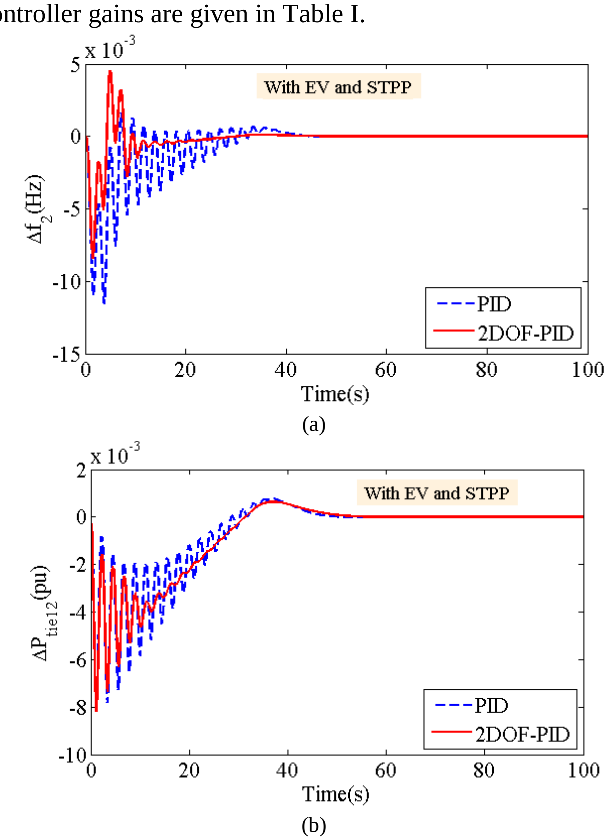


Fig. 4. Dynamic response comparison under nominal condition with 2DOF-PID and PID controller (a) Δf_2 vs. time, and (b) ΔP_{tie12} vs. time

The comparison of the system responses obtained using the controllers are shown in Fig. 4. It is observed from the figures that the performance of 2DOF-PID controller is better than PID controller. The values of peak deviations and setting time are noted down in Table II.

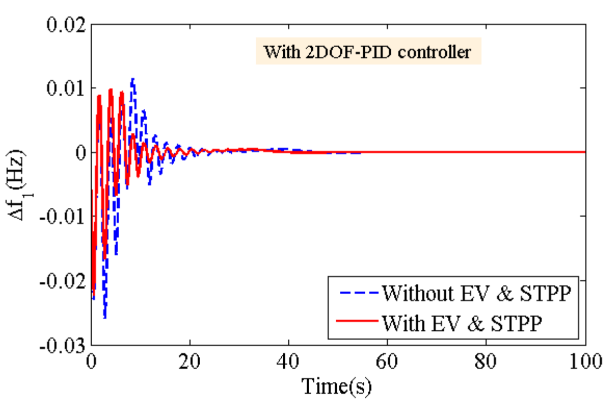
TABLE I
OPTIMUM VALUES OF GAINS OF SECONDARY CONTROLLER

Controller	Gains	Optimum values		
		Controller 1	Controller 2	Controller 3
2DOF-PID	K_{Pi}^*	0.737718	0.900677	0.979649
	K_{Ii}^*	0.700257	0.719086	0.825839
	K_{Di}^*	0.957445	0.407558	0.441662
	b_i^*	0.915818	0.644932	0.763588
	c_i^*	0.921305	0.044962	0.875061
PID	K_{Pi}^*	0.040481	0.043009	0.725191
	K_{Ii}^*	0.978787	0.890446	0.257062
	K_{Di}^*	0.696692	0.030151	0.951152

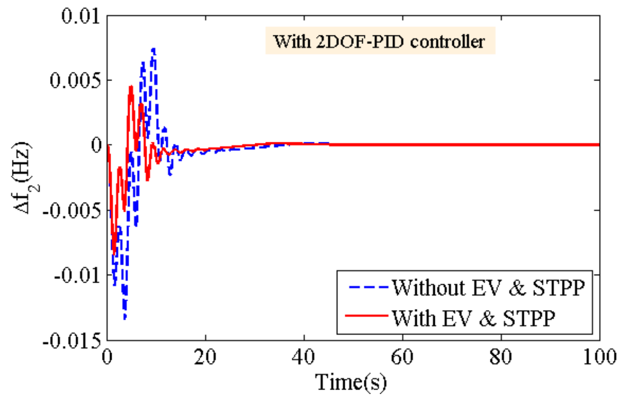
TABLE II
VALUES OF SETTLING TIME, PEAK OVERSHOOT AND PEAK UNDERSHOOT FOR FIG. 4

	Controller	Fig. 4(a)	Fig. 4(b)
Settling time	2DOF-PID	40.92	49.9
	PID	54.42	52.01
Peak over-shoot	2DOF-PID	0.004539	0.0006264
	PID	0.001481	0.0007609
Peak under-shoot	2DOF-PID	0.008074	0.008088
	PID	0.0115	0.007888

The impact of integrating PEVs and STPP to the power system has also been tested in this section. For this, the dynamic responses obtained in the presence of PEVs and RES are compared with those obtained in their absence and presented in Fig. 5. It can be clearly seen from the comparison that the presence of PEVs and RES gives better responses than that in its absence in terms of peak deviations, and number of oscillations, and hence proves its efficacy in frequency regulation.



(a)



(b)

Fig. 5. Dynamic response comparison under nominal condition in presence and absence of PEVs and STPP

(a) Δf_1 vs. time

(b) Δf_2 vs. time

B. *Under simultaneous perturbation*

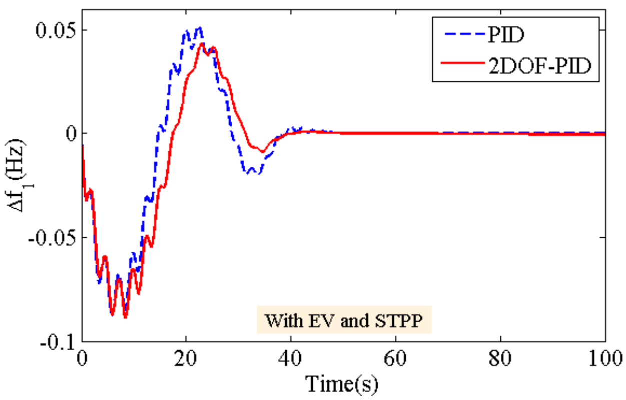
In the section discussed above, the studies are carried out under nominal system conditions, and 1% SLP was assumed to be present only in one area. In this section, studies are made with 1% SLP applied in initially two areas, then, in all the three areas. The controller gains are optimized by using WDO for both SLP in two areas and SLP in three areas, and the optimized values are tabulated in Table III and Table IV respectively. A comparison between the responses so obtained by using 2DOF-PID and PID controller when SLP is applied in two areas and three areas are depicted in Fig. 6.

TABLE III
OPTIMUM VALUES OF GAINS OF SECONDARY CONTROLLER

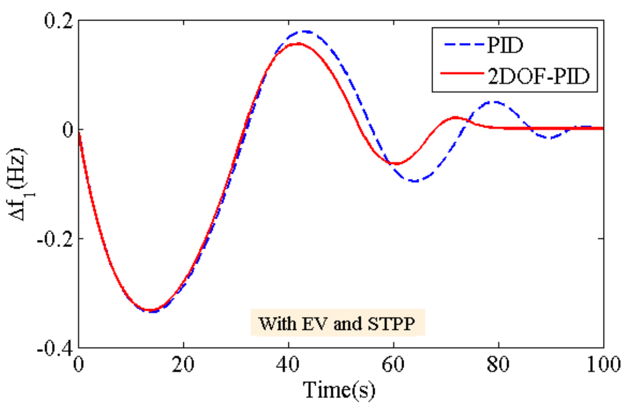
Controller	Gains	Optimum values		
		Controller 1	Controller 2	Controller 3
2DOF-PID	K_{Pi}^*	0.675831	0.007789	0.858975
	K_{Ii}^*	0.435443	0.938024	0.138503
	K_{Di}^*	0.943510	0.554219	0.447589
	b_i^*	0.982413	0.199901	0.250916
	c_i^*	0.904667	0.564501	0.640587
PID	K_{Pi}^*	0.757045	0.787848	0.869192
	K_{Ii}^*	0.650749	0.678601	0.674228
	K_{Di}^*	0.271620	0.491709	0.080258

TABLE IV
OPTIMUM VALUES OF GAINS OF SECONDARY CONTROLLER

Controller	Gains	Optimum values		
		Controller1	Controller2	Controller3
2DOF-PID	K_{Pi}^*	0.933722	0.218991	0.869969
	K_{Ii}^*	0.140219	0.311820	0.243375
	K_{Di}^*	0.863559	0.751537	0.209961
	b_i^*	0.870857	0.507137	0.327700
	c_i^*	0.086355	0.822310	0.494727
PID	K_{Pi}^*	0.266608	0.099653	0.155148
	K_{Ii}^*	0.138527	0.255283	0.873733
	K_{Di}^*	0.322760	0.327014	0.372280



(a)



(b)

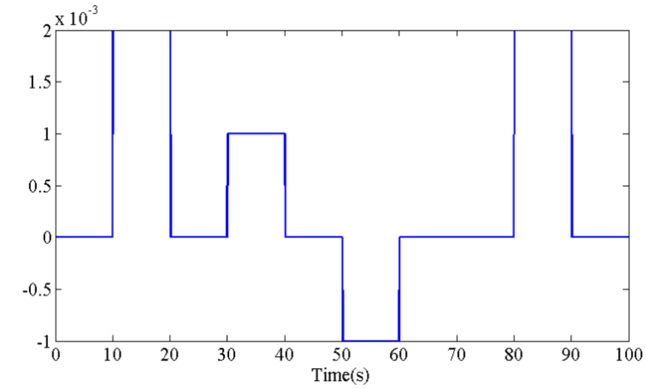
Fig. 6. Dynamic response comparison under simultaneous perturbation with 2DOF-PID and PID controller
(a) Δf_1 vs. time with 1% SLP in two areas
(b) Δf_1 vs. time with 1% SLP in three areas

C. *Under random load perturbation*

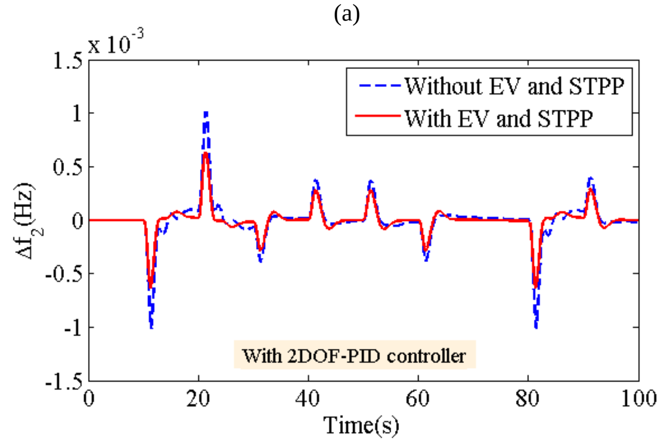
The efficiency of PEVs and RES in frequency regulation under nominal condition and simultaneous perturbation has been tested, and also has been proved to be very effective. In this section, an attempt has been made to study the impact of PEVs and RES under random loading condition. The optimized values of the gains of 2DOF-PID controller are listed in Table V. The frequency responses of the system in the presence and absence of PEVs and RES are compared and presented in Fig. 7. It can be concluded from the figures that in the absence of PEVs and RES the responses are deteriorated from those obtained in their presence. Hence, it is evident from the analysis that integration of PEVs and RES to the conventional system may contribute in frequency regulation.

TABLE V
OPTIMUM VALUES OF GAINS OF SECONDARY CONTROLLER

Controller	Gains	Optimum values		
		Controller 1	Controller 2	Controller 3
2DOF-PID	K_{Pi}^*	0.728626	0.841834	0.116807
	K_{Ii}^*	0.943821	0.866799	0.296691
	K_{Di}^*	0.695063	0.554388	0.122059
	b_i^*	0.259041	0.729381	0.524671
	c_i^*	0.386029	0.106010	0.906882



(a)



(b)

Fig. 7. (a) Random load pattern applied
(b) Δf_2 vs. time at random loading condition with and without PEVs and STPP

IV. CONCLUSION

This paper presents an aggregate model of a multi-area system with thermal system, plug-in electric vehicles (PEVs) and solar thermal power plant (STPP) in Area-1, and thermal system and PEVs in Area-2 and Area-3. The application of Wind Driven Optimization technique optimized two degree of freedom Proportional-Integral-Derivative (2DOF-PID) is made in this presented work. The performance of 2DOF-PID controller is compared with that of Proportional-Integral-Derivative (PID) controller under different system conditions. It is revealed from the comparison that 2DOF-PID outperforms PID controller. The impact of integration of PEVs and STPP has been tested under nominal system condition and random perturbation. It is evident from the results that the integration of PEVs and STPP to the conventional system may be very effective in frequency regulation and can be employed for load frequency control.

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