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Automatic Generation Control Including Solar Thermal Power Generation with Fuzzy-PID Controller with Derivative Filter

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Abstract- The proposed research article presents an optimum Fuzzy-PID controller with a derivative filter (Fuzzy-PIDF) to stabilize the frequency in an interconnected power system which includes renewable sources of energy like solar thermal power generating units. The scrutinized system consists of two area unified power system where each area is consisting of a thermal unit with reheat turbine and a solar thermal unit. The automatic generation control is exercised in each area with the help of two distinct Fuzzy-PIDF controllers. A novel optimization method named the Grey Wolf Optimizer is applied for optimizing the coefficients of the proposed fuzzy-PIDF controller. A time dependent objective function (Integral Time Absolute Error) has been employed in this case as fitness function. Different controllers such as PID, Fuzzy-PID and Fuzzy-PIDF are used to stabilize the frequency oscillation as well as tie-line power variation in the multi-area system subjected to a disturbance of 0.01 p.u. in the system. The efficacy of the recommended Fuzzy-PIDF controller is also established in view of various time domain specifications like minimum undershoots, settling time and maximum overshoots. To check the robustness and sensitiveness of the controller, the system is subjected to random loading and parameter variations.

Keywords Fuzzy Logic Controller, Solar Energy, Grey Wolf Optimization, Automatic generation control, Fuzzy-PIDF Controller.

1. Introduction

The main objective of Automatic Generation Control in a traditional power system is to ensure a stable power system operation and to maintain the quality and reliability of the power being dispatched to the customers. A complete review of the AGC concepts and its various aspects are listed down in [1-2]. In the modern scenario, a power system is subdivided into various areas connected together with the help of tie-lines. The power system stability necessitates the perturbations in tie-line power and the frequency to be minimized and to be kept within their nominal values due to the occurrence of any sudden load changes in either area. A sudden deviation in the load demand of a particular area brings about a shifting in the stable operating point of the system and hence the frequency and the tie-line power exchange undergo a deviation from the normal values. The role of the AGC is to minimize the area control error (ACE) and force it to zero for minimizing the frequency deviancy and the tie-line power flow deviancy. In an organized power system, the role of AGC has been described in [3-5].

All the above studies and findings in the field of AGC done so far has been with the consideration that the power system considered contains only conventional sources of energy like thermal, hydro, hydro-thermal etc. Due to the growing concerns about the greenhouse effect, the heating up of the earth’s atmosphere and the increase in the rate of carbon emissions, environmentalists all over the world have been stressing towards the use of non-conventional and non-polluting sources of energy. The most common non-conventional sources of energy are the solar and the wind. The Solar energy and the wind energy over the recent years have discovered the huge potential in themselves. The integration of non-conventional energy sources in an interconnected power system harnesses the immense potential possessed by the renewable energy sources. The basic literature is mentioned in [6], describing how to model and integrate the renewable sources in an interconnected power system. Extensive research has been done to address the problems that arise due to the inclusion of renewable sources in an interconnected power system. The effect of photovoltaic power generation on the frequency and generation control of a system is elaborately discussed in Paper [7]. Further in 2010 a brief survey was conducted regarding the load frequency control (LFC) issues caused due to the integration of renewable resources in an interconnected power system [8]. Articles [9] and [10] effectively address the load frequency issues due to the inclusion of renewable generating sources in an interconnected power system under various conditions.

The main control action of the AGC is to reduce the area control error (ACE) to zero. This stage requires the help of controllers. Conventional controllers like PI controller, PID controller and many others found its application in AGC. However the performance of these classical controllers is restrained in case there is a change in the operating point of the system. So in order to overcome this shortcoming, aid has been taken to implement various soft computing tools in order to establish a smooth control action. The inclusion of fuzzy logic controller for the control of the power system was illustrated in Paper [11]. Article [12] draws a comparative study between the classical PID controllers and the Fuzzy Logic Controller when applied to the AGC in an organized power system. Use of evolutionary computation technique and swarm intelligence to tune the controller parameters become the recent practice. Papers [13-15] effectively and elaborately describe the use of evolutionary based computation and soft computing techniques like Firefly Algorithm, Hybrid Differential Evolution-Pattern Search technique, Bacterial Foraging technique for the AGC in a unified power system. A comparative description of artificial bee colony optimization technique for the AGC of an interconnected hydrothermal power system is effectively projected in [16]. A hybridization of soft computing with the Fuzzy logic controller along with PID controller was done and applied effectively in the AGC of a unified power system [17]. Articles [18-20] explain the modelling of solar field and their application in many engineering fields. Papers [21-23] deal with the study of design of Load frequency controller in microgrid and concentrate on the effect of the integration of solar and wind energy in a power system when operating in islanded mode. Paper [24] focuses on the use of power electronics for renewable energy systems and mainly concentrates on solar and wind power system. The issues of overtime voltage scheduling and real time control action in case of distrubuted generation systems are addressed in [25-26]. In [27] the effect of hydrogen storage-transportation system to the frequency regulation of a microgrid is efficiently addressed. The effect of solar integration in distributed generation system is vividly studied under deregulated scenario [28].

This research paper proposes a novel controller called Fuzzy-Proportional Integral Derivative controller with derivative filter (Fuzzy-PIDF), being applied for the AGC in an interconnected power system. The two area system considered here proposes an integration of a solar thermal power unit along with the conventional thermal power unit in each area. The gains of the PID controller, Fuzzy-PID controller and Fuzzy-PIDF controller are tuned with Grey wolf Optimization technique. Hence the key objective of the proposed work can be summarized as follows:

- Modelling an interconnected power system with renewable sources of generation which includes solar thermal power generation along with conventional thermal power generation.
- Implementing PID controllers, Fuzzy-PID controllers and Fuzzy-PIDF controllers tuned by Grey Wolf Optimization for automatic generation control.
- Comparing the transient performance of the system with different controllers in terms of some performance parameters and hence establishing the supremacy of the suggested Fuzzy-PIDF controller.

2. System Investigated

The proposed work has taken into consideration a two area system of 2000 MW each consisting of a thermal power unit and a solar thermal power unit in both areas. Figure 1 demonstrates the model of the proposed system. The thermal unit comprises of a governor, a turbine and a reheat system. The solar thermal unit consists of a solar module, a governor and a turbine system as clearly depicted in the figure. The transfer function representations of the governor, turbine, reheat, solar plant are vividly mentioned in the aforesaid figure. Here T_g stands for the time constant of the governor and T_t stands for the time constant for the turbine. K_r stands out as the gain of the reheat system and T_r stands out as the time constant of the reheat system. K_p denotes the gain of the power system load or generator and T_p stands for the time constant of the power system. K_{SO} and T_{SO} stand out for the gain and the time constant of the solar unit respectively.

The Fuzzy-PIDF controller plays the role of secondary controllers here. Two Fuzzy-PIDF controllers have been introduced into the system. The controller gains and the fuzzy scaling factors have been optimized using a recent optimization scheme called the Grey Wolf Optimization technique. The objective function considered here is the Integral Time Absolute Error (ITAE) and can be denoted as

$$J = \int_0^t t\left(|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|\right)dt \tag{1}$$

3. Solar Field

Solar energy is known to have immeasurable potential that needs to be harnessed. There are countable numbers of systems that are known to utilize this huge potential and helps in the generation of power from them. Such devices

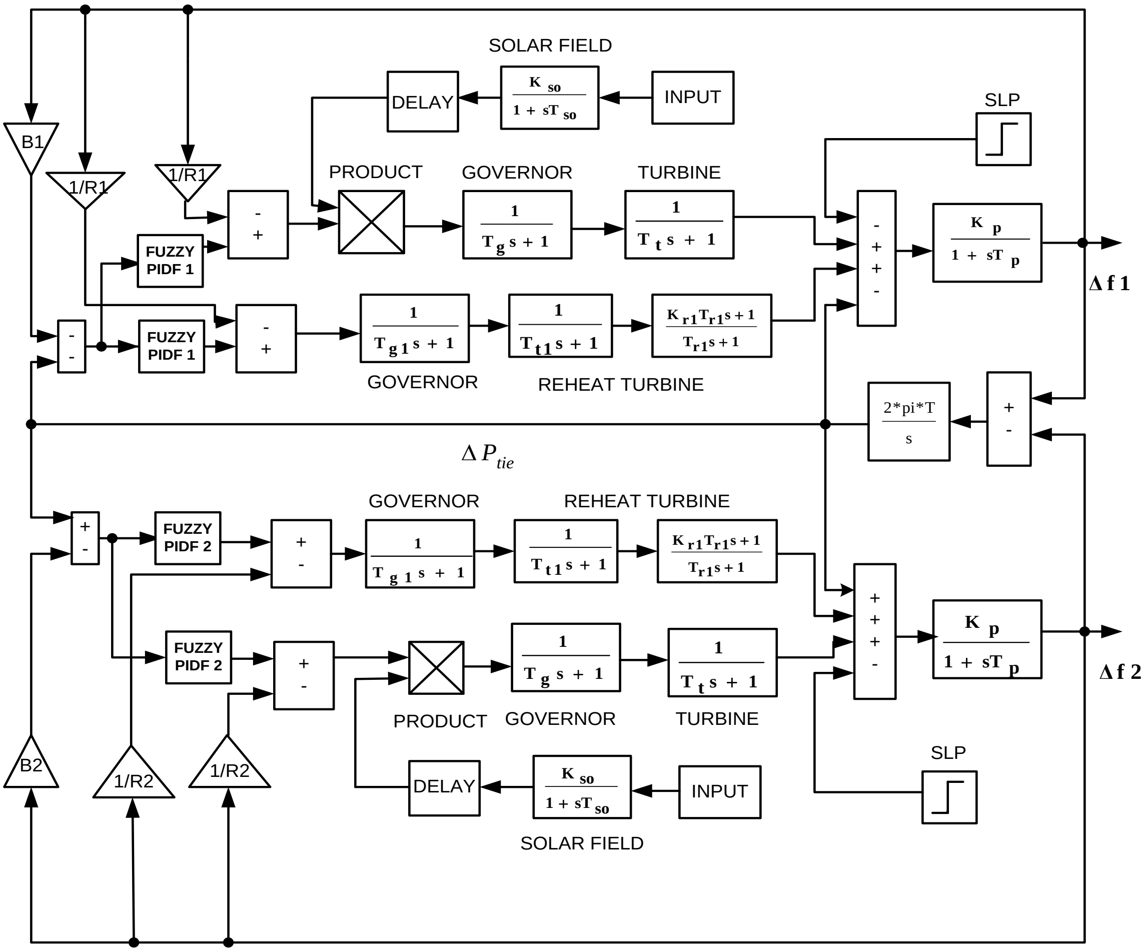

Fig. 1. The transfer function model of the proposed system

include Photovoltaic cells (PV cells) and Concentrated Solar Power (CSP). Paper [18] describes about the exploration of power generation by the solar field with different kinds of collectors. The prime objective of the collectors is the convergence of the solar rays to the pipes that transfer the working fluids. The working fluid then finds its application in the heat exchanger. A direct method of steam generation in solar boilers has also been proposed by Valenzuela et al [19]. The advent of technology and constant research also give rise to the idea of a hybrid solar power plant. The modelling of the solar power plant first needs the modelling of the solar field. The mathematical modelling of the solar field was proposed by Buzas et al [20].

The following equations describe the modelling of solar field.

$$\frac{dT_0(t)}{dt}=\frac{A\eta_0}{C}I(t)-\frac{U_LA}{C}\left[T_a(t)-T_e(t)\right]+\frac{v(t)}{V}[T_0(t)-T_e(t)] \qquad (2)$$

Where $T_a(t)=\dfrac{T_i(t)+T_0(t)}{2}$

The above equation (2) denotes the rate of change of output temperature. For the sake of simplicity the flow rate of the working fluid is assumed unchanged. Thus the above equation can be replaced as:

$$\frac{dT_0(t)}{dt}+\left[\frac{U_LA}{2C}+\frac{v}{V}\right]T_0(t)=\frac{A\eta_0}{C}I(t)+\left[\frac{v}{V}-\frac{U_LA}{2C}\right]T_i(t)+\frac{U_LA}{2C}T_e(t) \qquad (3)$$

The above equation when put through the Laplace operator gives us

$$T_0(s)=\frac{T_{so}}{T_{so}+1}\frac{A\eta_0}{C}I(s)+\frac{T_{so}}{T_{so}+1}\left[\frac{v}{V}-\frac{U_LA}{2C}\right]T_i(s)+\frac{T_{so}}{T_{so}+1}\times\frac{U_LA}{2C}T_e(s) \qquad (4)$$

Where the time constant of the solar field is demonstrated by T_{so} and $T_{so}=1/\frac{U_LA}{2C}+\frac{v}{V}$

Being very small, the inlet temperature and the environment temperature variation can be neglected. Hence the mathematical model of the solar field using Laplace operators with respect to solar irradiance can be expressed as:

$$G(s)=\frac{K_{so}}{1+T_{so}s} \qquad (5)$$

Here K_{so} can be denoted as the solar field gain. Hence the steam produced in the heat exchangers can be used to drive the turbine. In many cases a two second delay is also taken into consideration for many processes of the solar thermal power plant.

4. Proposed Controller (Fuzzy-PIDF Controller).

Owing to its simplicity, robustness and ease of control, the PID controllers became the prima facie controller in the industrial process organization. But with the increase in the complexity of control action and due to time constraints in plants, the conventional PID controller started losing its hold and became less convenient. Adding to that, these controllers were put to shape based on a single operating point. With the shift in this operating point the entire controller parameters need to be updated. In order to overcome this tedious job of updation of parameters with change in operating points, various soft computing tools were developed. The proposed work introduces a Fuzzy Logic based controller to address the problem. A soft computing tool, i.e. Fuzzy Logic Controller (FLC) is a computational method which depends on linguistic technique to compute a better solution. The Fuzzy method is mainly used when the conventional method proves to be futile. Figure 2 vividly demonstrates the architecture of the suggested Fuzzy-PID controller with derivative filter. In order to distinguish the Fuzzy-PIDF controller from Fuzzy-PID controller and PID controller, the architecture of both the Fuzzy-PID controller and PID controller are shown in the Fig.3 and Fig.4 respectively.

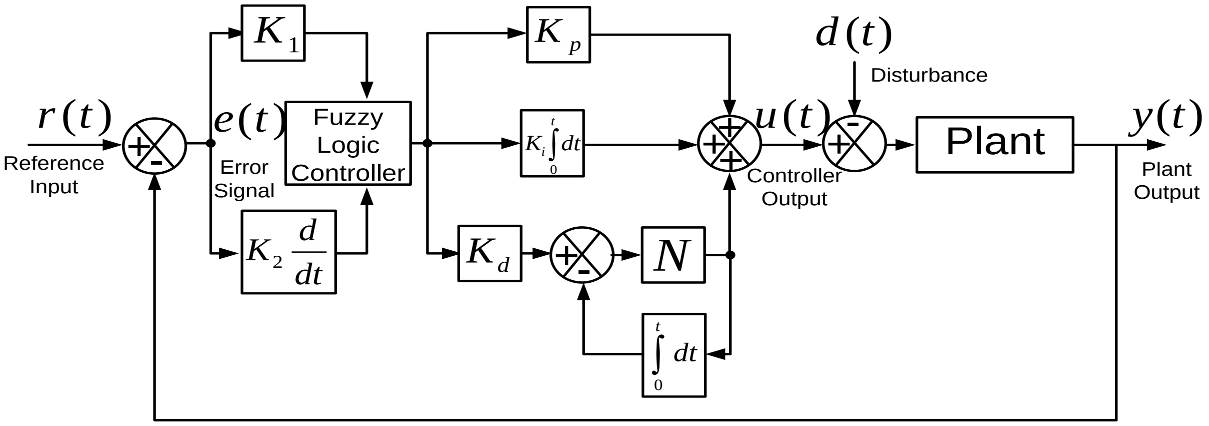

Fig. 2. The proposed Fuzzy-PID controller with derivative filter.

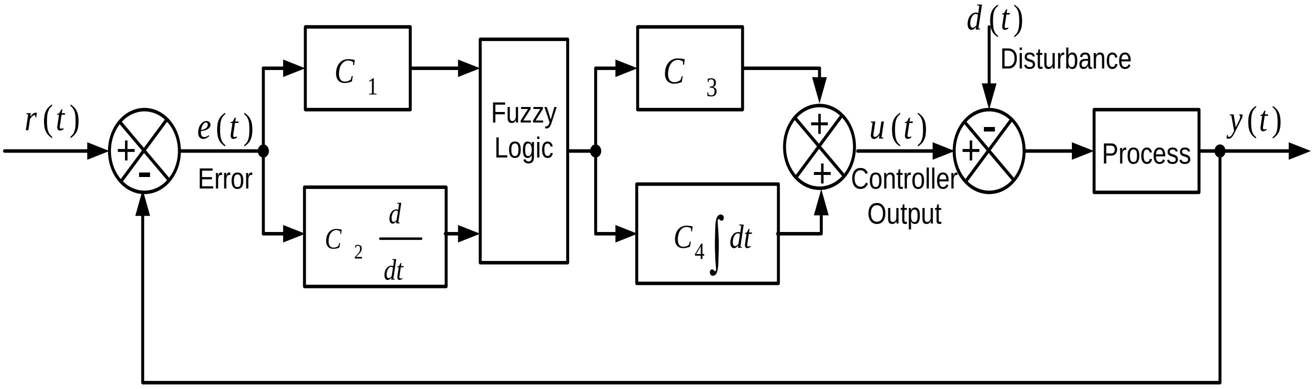

Fig. 3. Architechure of Fuzzy-PID controller without derivative filter.

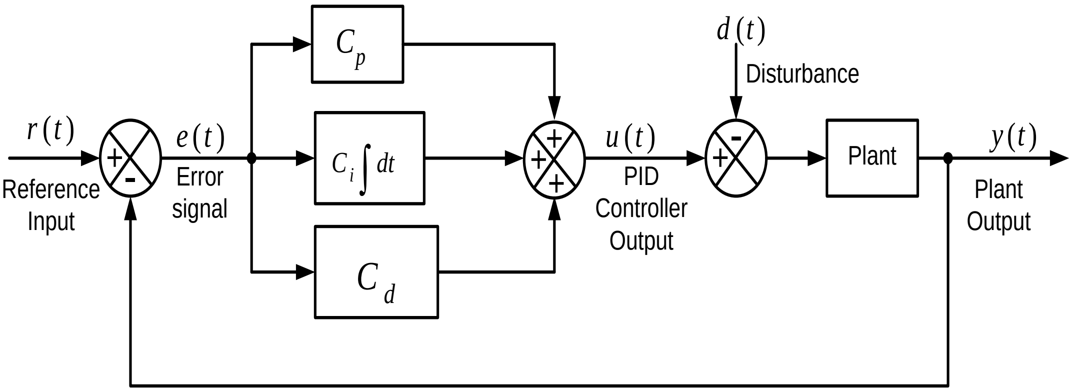

Fig. 4. Structure of PID controller.

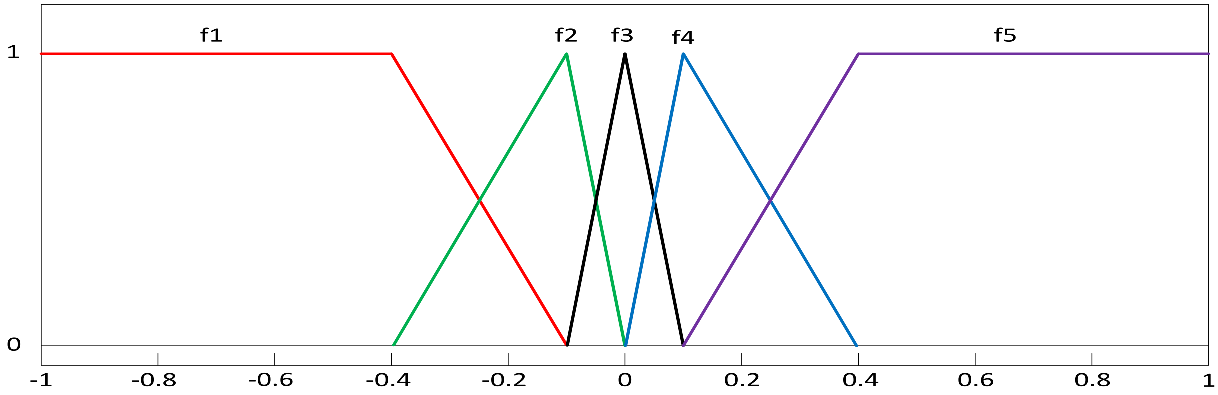

Fig. 5. Fuzzy Membership functions

From the Fig.2-4 it is clear that PID controller has three gain parameters (C_p, C_i, C_d), the Fuzzy-PID controller has four scaling parameters (C_1, C_2, C_3, C_4) and the Fuzzy-PIDF controller comprises five scaling factors (K_1, K_2, K_p, K_i, K_d) along with a filter coefficient (N). The derivative filter is included in the Fuzzy-PID controller so as to eliminate the undesirable signal or noise. The addition of filter in the Fuzzy-PID controller increases the performance of the control action.

The input to the Fuzzy-PIDF controller is mainly the Area Control Error (ACE) of the respective area. The proposed Fuzzy-PIDF controller considered five membership functions namely f_1, f_2, f_3, f_4 and f_5. Based on these five membership functions 25 rules have been formulated in the rule-base as shown in the Table 1. The fuzzy rule-base is based on the Mamdani fuzzy inference system. Figure 5 shows the fuzzy membership functions that govern the FLC and gives out the required outputs. In the proposed paper optimization of the constants of the suggested Fuzzy-PIDF controller is done by a newly accepted novel optimization technique called the Grey Wolf optimization technique.

Table 1. Fuzzy Rule Base

$\dot{e}$ e	*f1*	*f2*	*f3*	*f4*	*f5*
f1	*f1*	*f1*	*f2*	*f2*	*f3*
f2	*f1*	*f2*	*f2*	*f3*	*f4*
f3	*f2*	*f2*	*f3*	*f4*	*f4*
f4	*f2*	*f3*	*f4*	*f4*	*f5*
f5	*f3*	*f4*	*f4*	*f5*	*f5*

5. Grey Wolf Optimization

The social hierarchy of leadership stands out as the inspiration behind the formulation of the Grey Wolf Optimizer, introduced in 2014. Being a member of the Canidae family, the grey wolves reside in the topmost level of the predator chain. They are also referred to as the apex predator. The wolves mainly residing in a pack of 5 to 6 inherently bears a great sense of social dominance hierarchy. This hierarchy has got a male and a female of each pack as the leader named as Alphas. The most important decisions like hunting, sleeping, etc. are entrusted to them. Their decisions are strictly followed by each member of the pack. The managerial capabilities of alphas place them as the dominant member of the pack. The subsequent group, second to the alphas in dominance are the betas. Subordinate to the alphas, they mainly provide assistance to the alphas in their act of taking all the important decisions. The ultimate tier of the pack named as the omegas. Being the underdogs, they used to be at the receiving end of all the frustration and anger of the higher tiers.

The main course of action of the grey wolves can be divided as:

- ➢ Stalking, pursuing and tackling the prey.
- ➢ Encompassing and folding off the distance from the prey unless it starts moving.
- ➢ Jumping on the prey when the time is proper.

Mathematically, the procedure of the encirclement of the wolves can be expressed as:

$$\vec{D} = \left|\vec{C}\vec{X}_p(t) - \vec{X}\right| \tag{6}$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A}.\vec{D} \tag{7}$$

$$\vec{A} = 2\vec{a}\vec{r}_1 - \vec{A} \tag{8}$$

$$\vec{C} = 2\vec{r}_2 \tag{9}$$

Here ‘t’ denotes the current iteration. $\vec{A}$ and $\vec{C}$ are the coefficient vectors and $\vec{X}$ is the current position of the grey wolf.

The ability to sense the exact position of the prey and hunting them down is what made the grey wolves a class apart. Mainly guided by the alphas, the hunting property of alphas, betas and deltas are mathematically expressed as:

$$\vec{D}_{\alpha} = \left|\vec{C}_1 \vec{X}_{\alpha}(t) - \vec{X}\right| \tag{10}$$

$$\vec{D}_{\beta} = \left|\vec{C}_2 \vec{X}_{\beta}(t) - \vec{X}\right| \tag{11}$$

$$\vec{D}_{\delta} = \left|\vec{C}_3 \vec{X}_{\delta}(t) - \vec{X}\right| \tag{12}$$

$$\vec{X}_1 = \vec{X}_{\alpha} - \vec{A}_1 \vec{D}_{\alpha} \tag{13}$$

$$\vec{X}_2 = \vec{X}_{\beta} - \vec{A}_2 \vec{D}_{\beta} \tag{14}$$

$$\vec{X}_3 = \vec{X}_{\delta} - \vec{A}_3 \vec{D}_{\delta} \tag{15}$$

$$\vec{X}(t+1) = \frac{\left(\vec{X}_1(t) + \vec{X}_2(t) + \vec{X}_3(t)\right)}{3} \tag{16}$$

The methodology of the grey wolf optimization technique can be listed down as follows:

a. Initialization of a random population X and initialization of the GWO parameters like a, A and C.
b. Evaluation of the fitness of each agent with the help of the objective function. The objective function considered here is the ITAE.
c. The present population is to be updated with the help of equation (16).
d. The new population is then further evaluated using the objective function.
e. Updation of the search agents, particularly X_{α}, X_{β} and X_{δ}. The GWO parameters are also to be updated.
f. If the stopping criterion is not reached, then repeat steps (c-e), else the program returns X_{α} as the best solution.

6. Result And Analysis:

The proposed work includes a Grey wolf optimizer for optimal tuning of the suggested Fuzzy-PIDF controller. The proposed two-area system integrated with renewable sources is simulated using Matlab Simulink. The GWO code has been scripted in Matlab for the optimization of the controller gains and the fuzzy scaling factors. The maximum iteration considered for this process is 100 and the total population size was taken to be 100. The objective function implemented in this paper is a time dependent objective function known as the Integral Time Absolute Error (ITAE) mathematically expressed by equation (1).

The proposed system was simulated under a variety of perturbations. The results are noted and the system dynamic performances are clearly observed. The various case studies involved in this work are discussed below.

6.1. Case 1: Under a load perturbation of 1%.

The proposed model is simulated under the effect of a Step Load Perturbations of 0.01 p.u. applied to area 1. In this condition the GWO technique is employed for optimizing the gains of PID controller, Fuzzy-PID controller and Fuzzy-PIDF controller.The optimum values of different controller gains obtained by GWO technique are listed in Table 2. The results of Fuzzy-PIDF controller are put to test with that of PID controller and Fuzzy-PID controller under an SLP of 1% in area 1. The transient performance of the recommended two area system under the action of the suggested controller is observed in terms of settling time, maximum overshoot and minimum undershoot. Figure 6, Fig.7 and Fig.8 depicts the variation of frequency in area 1 (Δf_1), variation of frequency in area 2 (Δf_2) and variation in tie-line power (Δp_{tie}) under an SLP of 0.01 p.u.

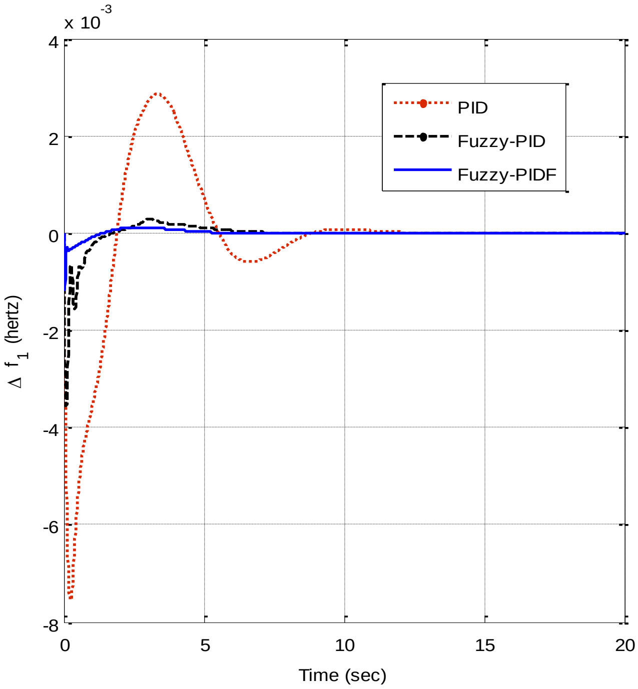

Fig. 6. Area 1 frequency deviations.

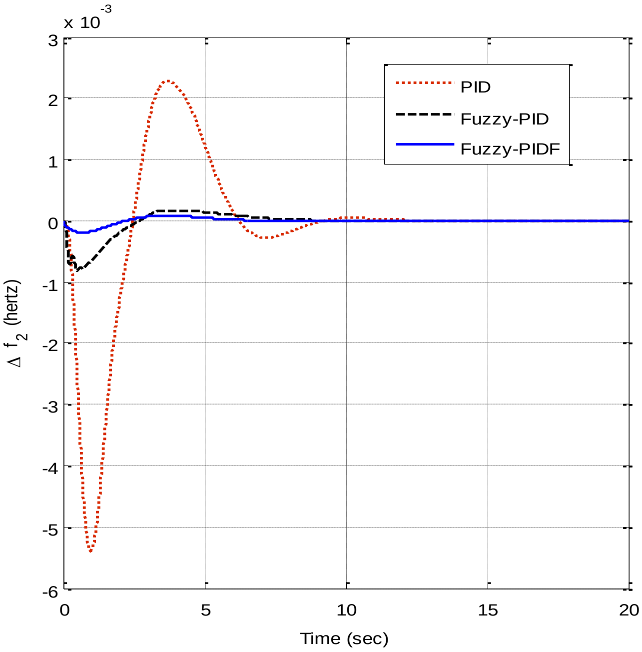

Fig. 7. Area 2 frequency deviations

Table 2. Optimized parameters of different controllers tuned by GWO technique.

<table>
<tr><th rowspan="2">Controller</th><th colspan="6">Area 1</th><th colspan="6">Area 2</th></tr>
<tr><th>K_1</th><th>K_2</th><th>K_p</th><th>K_i</th><th>K_d</th><th>N</th><th>K_1</th><th>K_2</th><th>K_p</th><th>K_i</th><th>K_d</th><th>N</th></tr>
<tr><td>Fuzzy-PIDF</td><td>4.0000</td><td>0.1000</td><td>2.4254</td><td>2.981</td><td>1.2909</td><td>250.375</td><td>3.3994</td><td>0.9514</td><td>3.1822</td><td>4.0000</td><td>2.3446</td><td>384.34</td></tr>
<tr><td rowspan="2">Fuzzy-PID</td><td colspan="2">C_1</td><td>C_2</td><td colspan="2">C_3</td><td>C_4</td><td colspan="2">C_1</td><td>C_2</td><td colspan="2">C_3</td><td>C_4</td></tr>
<tr><td colspan="2">1.8998</td><td>0.8992</td><td colspan="2">1.8987</td><td>1.8999</td><td colspan="2">1.979</td><td>1.7989</td><td colspan="2">1.1909</td><td>1.2934</td></tr>
<tr><td rowspan="2">PID</td><td colspan="2">C_p</td><td colspan="2">C_i</td><td colspan="2">C_d</td><td colspan="2">C_p</td><td colspan="2">C_i</td><td colspan="2">C_d</td></tr>
<tr><td colspan="2">2.3172</td><td colspan="2">4.0000</td><td colspan="2">2.0755</td><td colspan="2">2.2220</td><td colspan="2">0.0100</td><td colspan="2">0.3597</td></tr>
</table>

Table 3. Values of performance parameters of the system with different controllers.

Controller	Δf_1			Δf_2			ΔP_{tie}		
	$O_{sh}\times10^{-3}$ in Hz	T_s in sec	U_{sh} Hz	$O_{sh}\times10^{-3}$ in Hz	T_s in sec	U_{sh} Hz	$O_{sh}\times10^{-3}$ in p.u.	T_s in sec	U_{sh} p.u.
PID	2.9	10.8800	-0.0076	2.3	8.7800	-0.0054	0.8	7.0100	-0.0015
Fuzzy-PID	0. 3020	5.9700	-0.0036	0.1701	6.8600	-0.0008	0.0685	5.5500	-0.0003
Fuzzy-PIDF	**0. 1068**	**4.3300**	**-0.0012**	**0.0805**	**4.9400**	**-0.0002**	**0.0337**	**1.4300**	**-0.0001**

Table 4. Values of the performance parameters for the change in system parameters.

Parameters	**%age deviation**	T_s **for** Δf_1 **(in sec)**	$O_{sh}\times10^{-3}$ **for** Δf_1 **(in p.u.)**	U_{sh} **for** Δf_1 **(in p.u.)**	T_s **for** Δf_2 **(in sec)**	$O_{sh}\times10^{-3}$ **for** Δf_2 **(in p.u.)**	U_{sh} **for** Δf_2 **(in p.u.)**
R	**-20%**	4.3300	0.1066	-0.0012	4.9500	0.0802	-0.0002
	-10%	4.3300	0.1067	-0.0012	4.9400	0.0804	-0.0002
	+10%	4.3300	0.1069	-0.0012	4.9400	0.0806	-0.0002
	+20%	4.3300	0.1070	-0.0012	4.9400	0.0807	-0.0002
B	**-20%**	4.5800	0.1237	-0.0014	5.1600	0.1032	-0.0003
	-10%	4.4500	0.1141	-0.0013	5.0500	0.0907	-0.0002
	+10%	4.2200	0.1011	-0.0011	4.8200	0.0722	-0.0002
	+20%	4.1300	0.09651	-0.0010	4.7000	0.06511	-0.0002

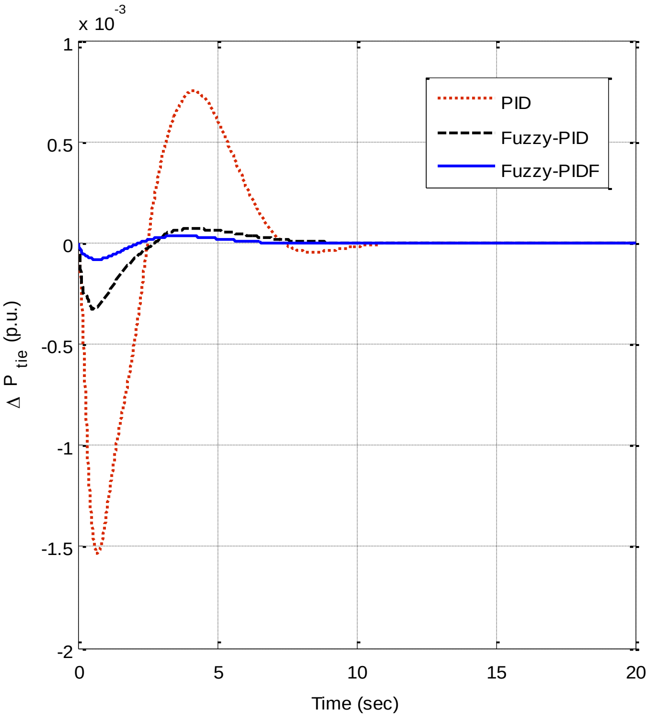

Fig. 8. Variations in tie line power flow.

From the Fig.6-8, it is clearly inferred that the Fuzzy-PID controller with derivative filter has been much more effective in bringing the transient state deviation to zero in the shortest span of time. Table 3 lists down the comparison of settling time, maximum overshoot and minimum undershoot using PID, Fuzzy-PID and Fuzzy-PIDF controller respectively. This table clearly depicts that the values of the performance parameters are the least in case of the proposed Fuzzy-PIDF controller thus establishing its supremacy.

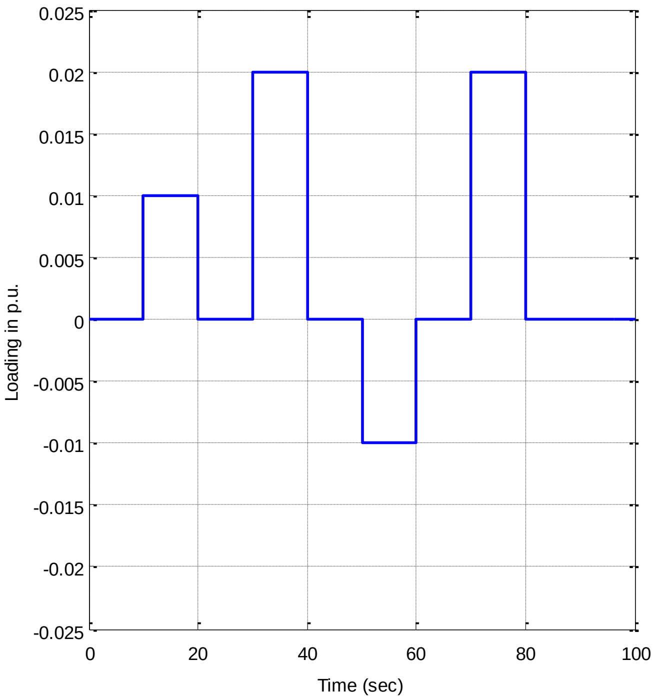

Fig. 9. Random Load Pattern.

6.2. Case 2: Under random loading conditions.

The analysis of the supremacy of the proposed controller is now done under the effect of random loading applied to area 1. The pattern of random loading is clearly demonstrated in Fig. 9. Figure 10, Fig.11 and Fig.12 exhibits the variation in frequency of area 1 (Δf_1), variation in frequency of area 2 (Δf_2) and variation in tie line power (Δp_{tie}) respectively under the action of random loading. The corresponding plots clearly depict that the proposed Fuzzy-PID controller with derivative controller has been effective in minimizing the transient state error faster than the PID and the Fuzzy-PID controller.

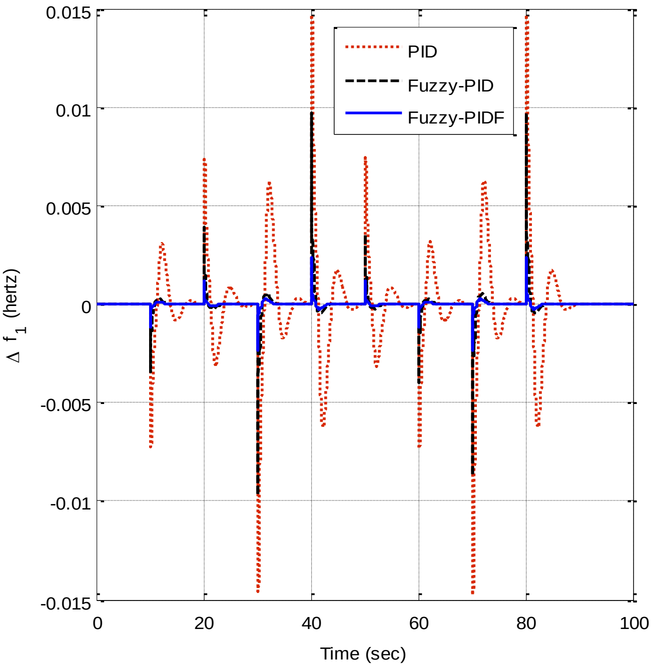

Fig. 10. Variation in frequency in area 1.

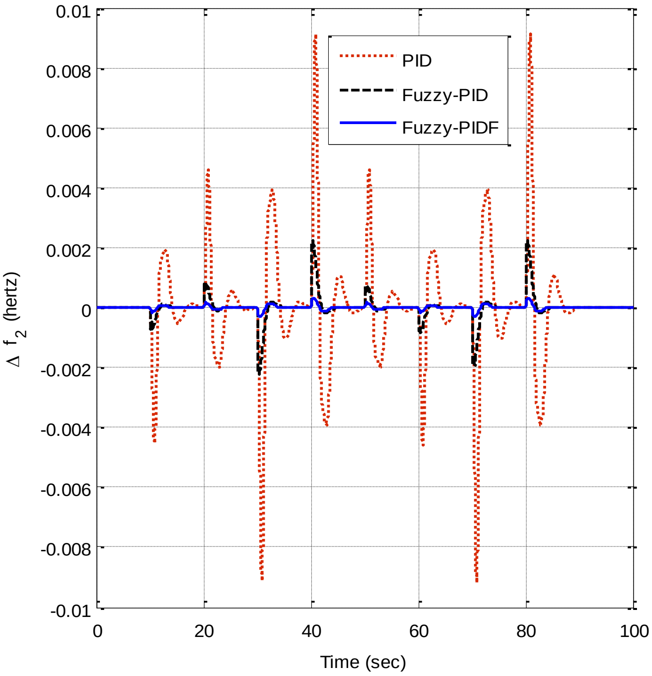

Fig. 11. Variation in frequency in area 2.

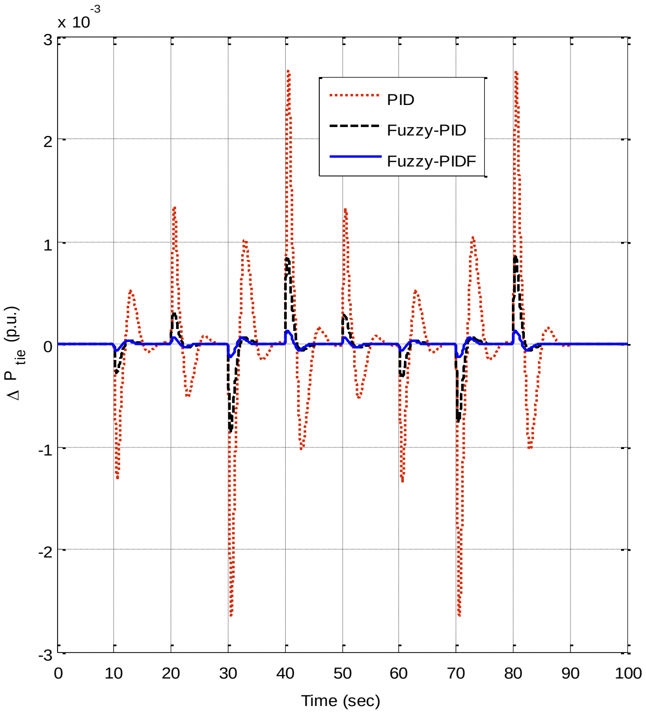

Fig. 12. Variations in tie line power flow.

6.3. Case 3: Under parameter variations.

The robustness analysis of the system is further investigated by bringing about a random change in system parameters mainly the frequency regulation constant R and the bias coefficient B. The values of these parameters are increased by 10 % and 20% and subsequently decreased by 10% and 20% to scrutinize the sensitiveness of the system. The dynamic performance was observed in each case and the values of settling time, maximum overshoot and minimum undershoot for Δf_1 and Δf_2 are listed down in Table 4. This table reveals that the performance parameters are not varying significantly even when the parameters of the system vary widely and hence establishes the efficacy and the supremacy of the proposed Fuzzy-PIDF controller over PID and Fuzzy-PID controller.

7. Conclusion

The proposed work consists of a power system with two areas, each area consisting of a thermal unit along with reheat and a solar thermal unit. Fuzzy-PIDF controller is employed as the secondary controller in the proposed system. The AGC model has in total four Fuzzy-PIDF controllers. All the PID controller gains, the Fuzzy-PID scaling factors and the Fuzzy-PIDF coefficients have been tuned by the Grey Wolf Optimizer technique. The proposed system is put to test under different abnormal conditions like an SLP of 0.01p.u., random loading pattern and change in system parameters mainly the frequency regulation constant R and the bias constant B. The dynamic performance of the system is observed in terms of performance parameters such as settling time, maximum overshoot and minimum undershoot and the results obtained are compared with the PID controller and the Fuzzy-PID controller. The results and the analysis done clearly puts to light that the proposed Fuzzy-PID controller with derivative filter is very much effective and superior in reducing the frequency deviations in respective areas along with the tie-line power variations to zero within a short span of time. The dynamic performances therefore strongly establish the supremacy of the proposed controller.

References

[1] P. Kundur, Neal J. Balu, and Mark G. Lauby, Power system stability and control, Vol. 7. New York: McGraw-hill press, 1994.

[2] O.L. Elgerd, Electric energy systems theory: an introduction, New York: McGraw-hill press, 1982.

[3] O.L Elgerd, C.E. Fosha, "Optimum megawatt-frequency control of multiarea electric energy systems", IEEE Transactions on Power Apparatus and Systems, Vol .4, pp. 556-563, 1970.

[4] P. Kumar, and D.P.Kothari, "Recent philosophies of automatic generation control strategies in power systems", IEEE transactions on power systems, Vol. 20, No. 1, pp. 346-357, 2005.

[5] H. A. S. H. Shayegi, H. A. Shayanfar, and A. Jalili, "Load frequency control strategies: A state-of-the-art survey for the researcher", Energy Conversion and management, Vol. 50, No. 2, pp. 344-353, 2009.

[6] A. Datta et al., "Load frequency control of a renewable energy sources based hybrid system", Systems, Process and Control (ICSPC), 2015 IEEE Conference Malaysia, pp. 34-38, 18-20 Dec. 2015.

[7] H. Bevrani, A. Ghosh, and G. Ledwich, "Renewable energy sources and frequency regulation: survey and new perspectives", IET Renewable Power Generation, Vol. 4, No. 5, pp. 438-457, 2010.

[8] H. Asano, K. Yajima, and Y. Kaya, "Influence of photovoltaic power generation on required capacity for load frequency control", IEEE Transactions on Energy Conversion, Vol. 11,No. 1, pp. 188-193, 1996.

[9] L. Wang, C.B. Huang, "Dynamic Stability Analysis of a Grid-Connected Solar-Concentrated Ocean Thermal Energy Conversion System", IEEE Transactions on Sustainable Energy, Vol. 1, No. 1, pp. 10-18, 2010.

[10] D.C. Das, A. K. Roy, and N. Sinha, "GA based frequency controller for solar thermal–diesel–wind hybrid energy generation/energy storage system", International Journal of Electrical Power & Energy Systems, Vol.43, No. 1, pp. 252-279, 2012.

[11] C.S. Indulkar, and B. Raj, "Application of fuzzy controller to automatic generation control", Electric machines and power systems, Vol. 23, No. 2, pp. 209-220, 1995.

[12] J. Nanda, and A. Mangla, "Automatic generation control of an interconnected hydro-thermal system

using conventional integral and fuzzy logic controller", Electric Utility Deregulation, Restructuring and Power Technologies, (DRPT 2004), China, pp. 372-377, 5-8 April 2004.

[13] S. Padhan, R.K. Sahu, and S. Panda, "Application of firefly algorithm for load frequency control of multi-area interconnected power system", Electric power components and systems, Vol.42, No. 13, pp.1419-1430, 2014.

[14] R.K. Sahu, S. Panda, and N. K.Yegireddy, "A novel hybrid DEPS optimized fuzzy PI/PID controller for load frequency control of multi-area interconnected power systems", Journal of Process Control, Vol. 24, No. 10, pp. 1596-1608, 2014.

[15] E.S. Ali, and S. M. Abd-Elazim, "Bacteria foraging optimization algorithm based load frequency controller for interconnected power system", International Journal of Electrical Power & Energy Systems, Vol. 33, No. 3, pp. 633-638, 2011.

[16] H. Gozde, M. C. Taplamacioglu, and I. Kocaarslan, "Comparative performance analysis of Artificial Bee Colony algorithm in automatic generation control for interconnected reheat thermal power system", International Journal of Electrical Power & Energy Systems, Vol. 42, No. 1, pp. 167-178, 2012.

[17] B.K. Sahu, S. Pati, and S. Panda. "Hybrid differential evolution particle swarm optimisation optimised fuzzy proportional–integral derivative controller for automatic generation control of interconnected power system", IET Generation, Transmission & Distribution, Vol. 8, No. 11, pp. 1789-1800, 2014.

[18] V.S. Reddy, S. C. Kaushik, K. R. Ranjan, and S. K. Tyagi, "State-of-the-art of solar thermal power plants—A review", Renewable and Sustainable Energy Reviews, Vol. 27, pp. 258-273, 2013.

[19] L. Valenzuela, E.D. Zarza, M. Berenguel, and E. F. Camacho, "Direct steam generation in solar boilers", IEEE control systems 24, Vol. 2, pp. 15-29, 2004.

[20] J. Buzás and R. Kicsiny, "Transfer functions of solar collectors for dynamical analysis and control design", Renewable Energy, Vol. 68, pp. 146-155, 2014.

[21] KUMAR, SENTHIL and A. Jeya Veronica, "Load Frequency Controller Design for Microgrid Using Internal Model Approach", International Journal of Renewable Energy Research (IJRER), Vol. 7, No. 2, pp.778-786, 2017.

[22] Yadav, Dinesh Kumar, T. S. Bhatti, and Ashu Verma, "Study of Integrated Rural Electrification System Using Wind-Biogas Based Hybrid System and Limited Grid Supply System", International Journal of Renewable Energy Research (IJRER),Vol. 7, No.1, pp.1-11, 2017.

[23] Jayalakshmi, N. S., D. N. Gaonkar, and Pramod Bhat Nempu, "Power Control of PV/Fuel Cell/Supercapacitor Hybrid System for Stand-alone Applications", International Journal of Renewable Energy Research (IJRER), Vol. 6,No. 2, pp.672-679, 2016.

[24] Choi, U. M., K. B. Lee, and Frede Blaabjerg, "Power electronics for renewable energy systems: Wind turbine and photovoltaic systems", Renewable Energy Research and Applications (ICRERA), 2012 International Conference on. IEEE, 2012.

[25] Zadeh, Alimorad K., et al., "Optimized day-ahead hydrothermal wind energy systems scheduling using parallel PSO", Renewable Energy Research and Applications (ICRERA), 2012 International Conference on. IEEE, 2012.

[26] Ziadi, Zakaria, et al., "Real time voltage control of unbalanced distribution systems with photovoltaic generation", Renewable Energy Research and Applications (ICRERA), 2012 International Conference on. IEEE, 2012.

[27] Morel, Jorge, et al., "Contribution of a hydrogen storage-transportation system to the frequency regulation of a microgrid", Renewable Energy Research and Applications (ICRERA), 2015 International Conference on. IEEE, 2015.

[28] Atia, Raji, and Noboru Yamada, "Distributed renewable generation and storage systems sizing in deregulated energy markets", Renewable Energy Research and Applications (ICRERA), 2015 International Conference on. IEEE, 2015.

Appendıx:

Nominal Parameters of the system are:
f=60 Hz; T_{g1} =0.08 s; T_{t1}=0.3 s, T_t=3.0 s; T_g=1.0 s; T_{r1}=10 s; K_{r1}=0.5; K_p=120 Hzpu MW pu MW/rad; H= 5s; D= $8.33*10^{-3}$ pu MW/Hz ; T_p= 20 s; T= 0.086; R_i=2.4 Hz/pu MW; B_i =0.425 pu MW/Hz; K_{so}=1.8, T_{so}=1.8 s.