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Optimal fuzzy-PID controller with derivative filter for load frequency control including UPFC and SMES

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ABSTRACT

A newly adopted optimization technique known as sine-cosine algorithm (SCA) is suggested in this research article to tune the gains of Fuzzy-PID controller along with a derivative filter (Fuzzy-PIDF) of a hybrid interconnected system for the Load Frequency Control (LFC). The scrutinized multi-generation system considers hydro, gas and thermal sources in all areas of the dual area power system integrated with UPFC (unified power flow controller) and SMES (Super-conducting magnetic energy storage) units. The preeminence of the offered Fuzzy-PIDF controller is recognized over Fuzzy-PID controller by comparing their dynamic performance indices concerning minimum undershoot, settling time and also peak overshoot. Finally, the sensitiveness and sturdiness of the recommended control method are proved by altering the parameters of the system from their nominal values and by the implementation of random loading in the system.

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1. INTRODUCTION

Being an integral part of modern energy management systems, Automatic generation control has a pivotal responsibility to play in a unified power system. Proper balancing between the aggregate power generation & the load demands of a particular area ensures the effective and positive operation of an interconnected power system [1]. Subject to a slight deviation of the load demand from normal prescribed values, the system shifts from its stable operating conditions. This shifting from the stable operating point gives rise to deviances in frequency along with tie-line power of interconnected areas. The primary goal of automatic generation control is to preserve frequency of the proposed modelled system within nominal limits. The AGC also makes it sure to ensure the correct exchange of power between interconnected areas.

Extensive literature survey conducted on this field of interest has brought to light several advancements that have been done over the course of time. In 1957, Cohn [2] put forward some theories regarding maintenance of interline power in an interconnected power system. Since then research on AGC has been advancing in a comparatively faster rate. Paper [3] lists down some comprehensive reviews regarding aAutomatic generation control effectively. The use of fuzzy control logic for the gain scheduling of the PID controllers and its use for the AGC control was proposed by Chang *et al*. [4]. Some recent philosophies related to automatic generation control for interconnected power system was suggested by Kothari *et al*. [5]. Paper [6] successfully elaborates the hybridization of swarm computation schemes like Particle Swarm Optimization using artificial intelligence like fuzzy logic controller for the tuning of the controller gains of the secondary controllers used in the interconnected power system. Paper [7] considered a hydro-thermal system for inspection as well as analyzed AGC of the system using classical controllers. But the use of conventional controllers had the major disadvantage of getting stuck in a single operating point. On subject to change in system conditions, the controller gains needed to be adjusted again. This problem was successfully solved in [8], which clearly elaborates the design of a controller based on artificial intelligence for the AGC of a thermal pus hydro system. Paper [9, 10] deals with the inclusion of various FACTs devices like TCSC, IPFC in the interconnected power system and deals with the AGC studies of the respective systems. Paper [11] also deals with the use of IPFC in the power system and studied the frequency controller of the system. Gains of the controller are tuned utilizing a hybrid pattern search-biogeographical based optimization technique. The concept of AGC under restructured market systems was successfully explained in [12]. Hybridization of the local-unimodal search & teaching and learning based optimization method is offered to tune the constraints of PID controller in an interconnected power system for AGC analysis [13]. The first use of newly accepted ant lion optimizing technique for tuning the controller gains of the secondary controllers used in AGC of the interconnected power system was proposed in [14]. The use of 2 DOF PID controller as a secondary controller and its optimization using TLBO technique is recommended in [15]. The study of AGC in a deregulated environment using a neuro-fuzzy technique to optimize controller gains is proposed in [16]. Papers [17, 18] deal with the application of modern optimization technique like edge theorem and differential evolution for the AGC of interconnected power systems. Paper [19] deals with the automatic generation control in an Energy park with the inclusion of a wind farm. In the article [20] hybrid algorithm named as DE-GWO is applied to adjust the fuzzy-based controller parameters of multiple unified systems.

The exhaustive literature survey has put to light that till date all the research works on LFC has been done without the integration of storage devices. This work proposes the Control mechanism to limit the oscillations in the frequency of the hybrid interconnected power system with SMES as an energy storing device along with UPFC as a secondary controller. This work also proposes a Fuzzy-PIDF controller applied to the LFC for the proposed model. The constraints related to Fuzzy-PID/ Fuzzy-PIDF controller structures are optimally tuned using a newly proposed technique for optimization named as Sine-Cos Algorithm. The primary motive of the proposed work is listed below:

a. Designing a multi-sourced system with UPFC and SMES.
b. Tune the parameters of the recommended controller using the sine-cosine algorithm.
c. Comparison of the system performance using Fuzzy-PIDF & Fuzzy-PID controller implemented in the designed hybrid power system.

Establishment of robustness of the implemented controller by scrutinizing the dynamic performance of the system under parameter variations and load variations.

2. SYSTEM SCRUTINIZED

Transfer function structure of the suggested hybrid power system along with UPFC and SMES is depicted in Figure 1. It consists of reheat thermal, hydro as well as gas generating units in each area. Fuzzy-PID controller with derivative filter is suggested for each of the units for the frequency regulation. In this hybrid interconnected power system, different types of parameters are used which are described in the nomenclature section. Here conventional generating sources are used along with SMES in each area. The UPFC and SMES are described in the next section. The deviation in the system is regulated while minimizing the ACE (Area Control error). The ACE presented in each of the areas is expressed as

$$ACE_1 = \Delta P_{tie1-2} + B_1 \Delta f_1 \text{ and } ACE_2 = \Delta P_{tie2-1} + B_2 \Delta f_2 \quad (1)$$

where ΔP_{tie} is the oscillation of interline power within both the areas, B_1 as well as B_2 are frequency bias coefficients of respective areas. Δf_1 along with Δf_2 oscillations of frequency in distinctive area.

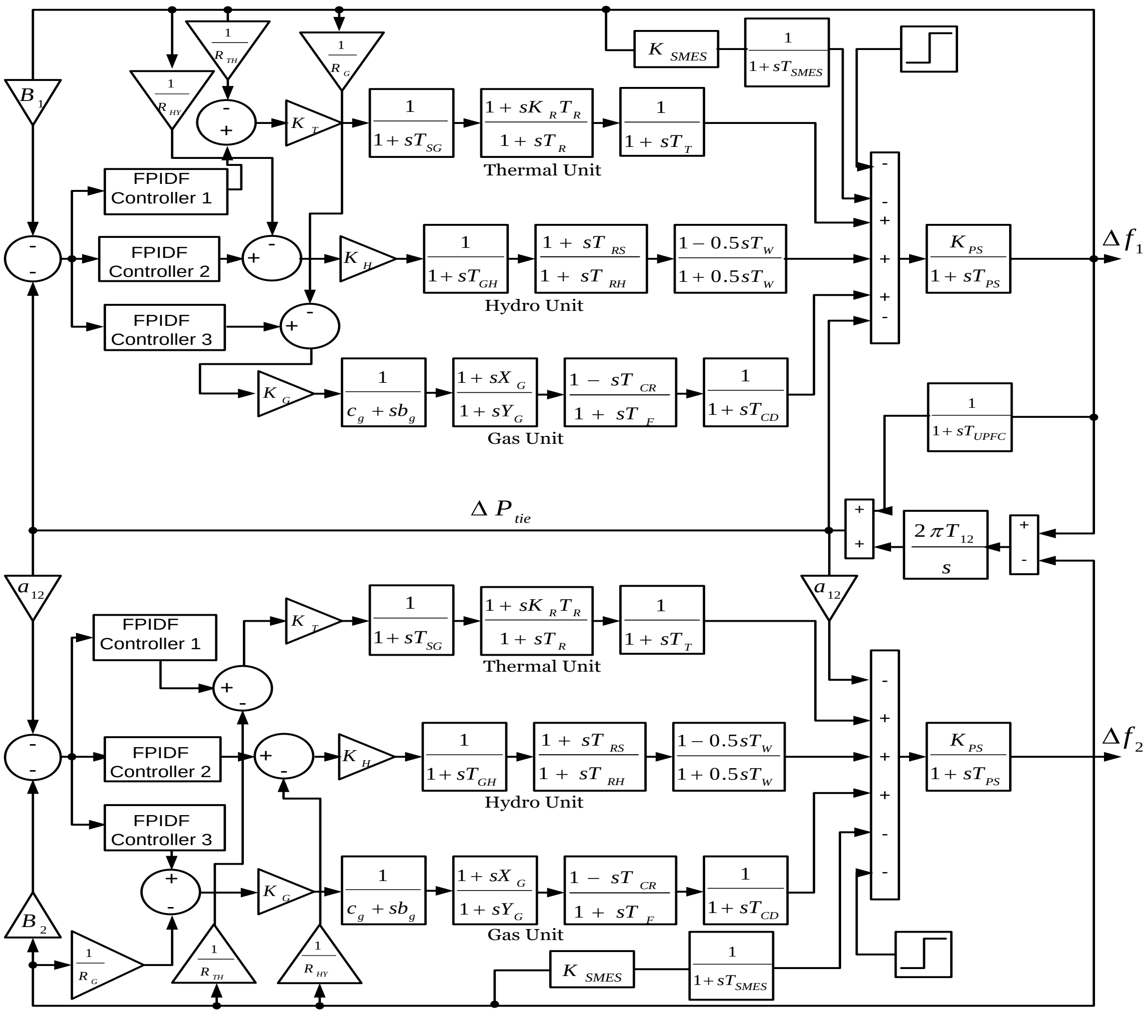

Figure 1. Power system model represented by transfer functions

2.1. Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage has the capability of storing electricity through the magnetic coil that consists of a superconducting wire near zero loss of energy. It enables to keep and discharge a large amount of power immediately. SMES helps to improve the quality of power by replacing voltage sags and power outages. It plays an imperative role to maintain grid reliability between renewable energy sources and transmission and distribution network. The parts of SMES like ac-dc converter, inverter-converter unit, and a step-down transformer are static in nature and gives better performances as compared to other power storage devices. It also includes superconducting coil and power conditioning system. Inverters or rectifiers are used to transform AC to DC in power conditioning system, and losses about (2-3) % occurred as compared to other storing energy devices. To improve the power quality, SMES quickly discharge AC power to the grid during an abrupt increase in demand of the load. The superconducting coil is charged to maintain the stability dirung disturbances. The magnetic energy gets stored indefinitely during charging condition. To attain the steady state value, the coil discharges the extra amount of energy to the network. The ability of quick discharge and time delay during charging makes SMES more different among all other energy storage devices. Except that high reliability of supply and less loss of power are the most important advantages of SMES. To maintain the system frequency to its nominal value, SMES are implemented in area-1 as well as in area-2. Perturbation in frequency (Δf) along with the variation in the control vector (ΔP_{SMES}) act as input and output of SMES controller respectively. The gains of SMES controller (K_{SMES}) and time constant (T_{SMES}) has to be optimized.

2.2. Unified power flow controller (UPFC)

Flexible AC transmission system (FACTS) based on power electronics technology helps in improving the quality of transmission by supplying inductive /reactive power to the grid. Unified power flow controller (UPFC) has the capability of suppressing the oscillations in power system to improve transient stability of the power system. Static synchronous compensator (STATCOM) plus static synchronous series compensator (SSSC) are coupled through a general DC voltage link in UPFC. Line reactance, phase angle, and voltage are the controllable parameters of UPFC. V_{se} and Φ_{se} are the series voltage magnitude and the phase angle of series voltage as exposed in the Figure 2. The real power needed by the series converter is maintained by injecting a suitable amount of shunt voltage by shunt converter. The below expression indicates the complex power at the receiving end of the line.

$$P_{real} - jQ_{reactive} = \bar{V}_r^* \left\{ \frac{\bar{V}_S + \bar{V}_{se} - \bar{V}_r}{j(x)} \right\} \tag{2}$$

Series voltage V_{se} can be controlled from 0 to $V_{se,\max}$ and ϕ_{se} can be varied between 0 and 360 degrees at any power angle. The representation of UPFC can be done by

$$\Delta P_{UPFC}(S) = \left\{ \frac{1}{1 + ST_{UPFC}} \right\} \Delta F(S) \tag{3}$$

T_{UPFC} is the time constant of UPFC.

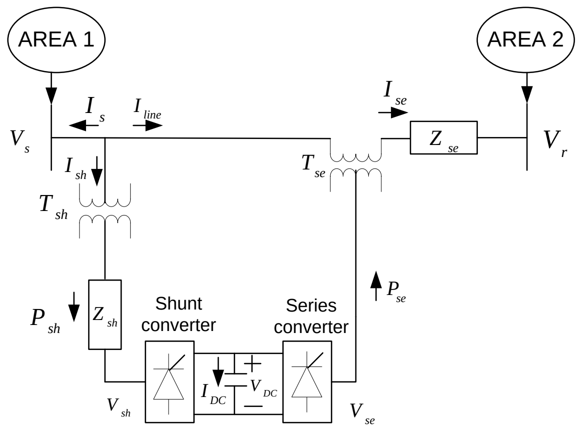

Figure 2. The connection of UPFC in a two area system

3. PROPOSED TECHNIQUE

3.1. Controller structure(fuzzy-PID controller without & with derivative filter)

Primarily PID controllers are planned to operate at a specified range of operating condition of the system, and operator manually can adjust the parameters according to the requirement of system. So this classical PID controller is not perfect for time-invariant plants having non-linearity & time-delay characteristics. So to overcome this problem Zadeh presented fuzzy logic controller based on the conception of computing with words which deals with the imprecision and uncertainties involved in the system. For better frequency regulation in this research article, we injected a derivative filter along with the fuzzy-PID controller. Figure 3 represents the outline of Fuzzy-PIDF controller. Figure 4 represents the five membership functions for input and output variables of Mamdani type fuzzy rule-based fuzzy logic system. The fuzzy rules of the suggested fuzzy controller are depicted in Table 1. Big negative (BN), small negative (SN), Zero (Z), Small positive (SP) & Big positive (BP) are five linguistic variables used for both input and output of the fuzzy system. Area controller error act as an input to the designed controller for this suggested two area power system shown in Figure 1. ACE is defined as the appropriate linear combination of deviations that occurs in frequency along with tie-line power for a particular area. The Equation (1) represents the ACEs of area1 & area2 respectively.

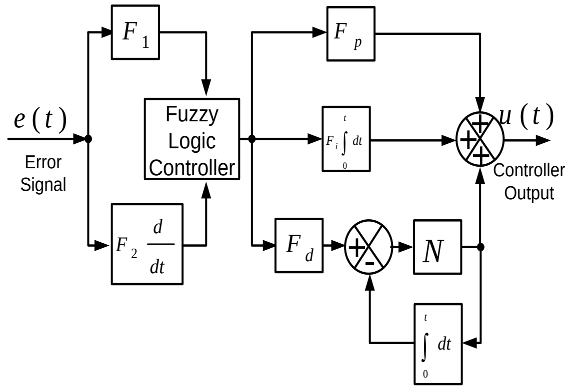

Figure 3. Construction Fuzzy-PID controller with derivative filter

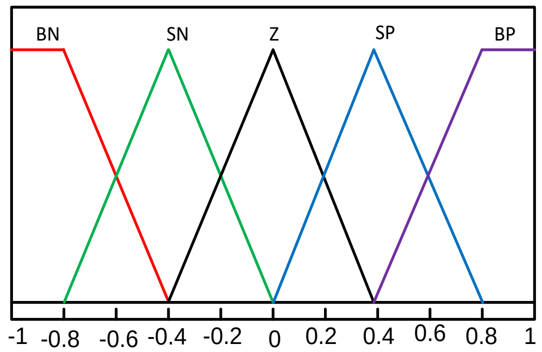

Figure 4. Triangular membership functions for the fuzzy controller

Table 1. Rule base for the fuzzy logic based controller

ACE	$\dot{ACE}$				
	BN	SN	Z	SP	PB
BN	BN	BN	BN	SN	Z
SN	BN	BN	SN	Z	SP
Z	BN	SN	Z	SP	BP
SP	SN	Z	SP	BP	BP
BP	Z	SP	BP	BP	BP

3.2. Sine cosine algorithm

On a general note, optimization techniques inspired by population behavior and social aspects start the optimization process with a set of random variables termed as the population. The random population is then weighed with the help of an objective/cost function and is put to improvement based on a set of rules. These rules form the heart of every optimization technique. It is the rules which make one technique different from the other. Since these population-based optimization techniques stochastically search for optimal solutions, it is not always apparent that the very first execution of the optimization program will give the optimal solutions. It might demand a series of repetitive runs to yield optimal solutions. Neglecting the differences between different rules in different optimizers, there is one thing that holds common to all i.e., the partitioning of the entire search process to two halves- exploitation and exploration respectively. In the proposed algorithm the position updation has been done by the following set of formulae.

$$X_i^{t+1} = X_i^t + r_1 \times \sin(r_2) \times \left| r_3 P_i^t - X_i^t \right| \quad (4)$$

$$X_i^{t+1} = X_i^t + r_1 \times \cos(r_2) \times \left| r_3 P_i^t - X_{ii}^t \right| \quad (5)$$

where X_i indicates the current position of the particle in i-th dimension, r1/r2/r3 stand for the random numbers, P_i represents the position of the target point at the ith dimension.

The objective/cost function presented by ITAE is used to tune the scaling factors along with proportional, integral and derivative gains of the fuzzy-PID controller. Terms for the ITAE objective function are outlined in the below equation.

$$J = ITAE = \int_0^t (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|) t.dt \tag{6}$$

4. RESULTS AND ANALYSIS

Initially, the transfer function model of two area interconnected power system having multi-source generations with UPFC & SMES is developed in MATLAB (R2016a) software. To eliminate the steady-state error, the constraints of Fuzzy-PID and Fuzzy-PIDF controller are tuned by sin-cos optimization technique. The design parameters of Fuzzy-PID and Fuzzy-PIDF controllers are taken in the range of [0.01-3.0]. The filter co-efficient 'N' has taken in the range of [1-300]. Population size is taken as 100 and as well as the maximum number of iteration is taken as 100. ITAE is used as an objective/cost function to tune the gains of the Fuzzy-PID and Fuzzy-PIDF controller which is expressed in Equation (6). In this research paper the system is analyzed under three circumstances namely; (1) A SLP of 0.01 p.u. is applied to area 1; (2) random load perturbation in area 1 and (3) system parameters variations like governor speed regulation (R) and frequency bias parameter (B).

Firstly the system is subjected a step load perturbation of 0.01p.u. and simulation results for change of frequency in area 1(Δf_1) and the change in tie-line power (ΔP_{tie}) are shown in Figure 5 and Figure 6 respectively. The optimized gains of fuzzy–PID and Fuzzy-PIDF controllers are depicted in Table 2.

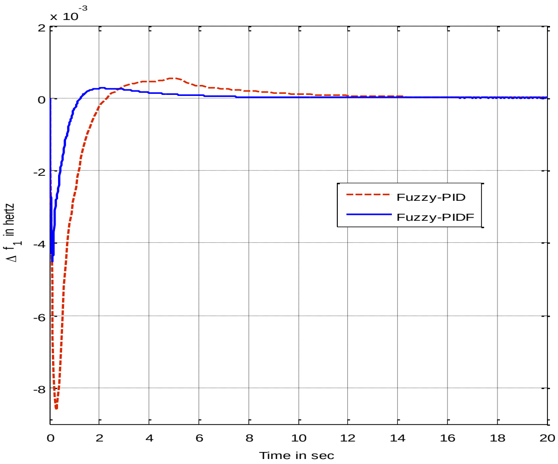

Figure 5. Oscillations of frequency in area 1

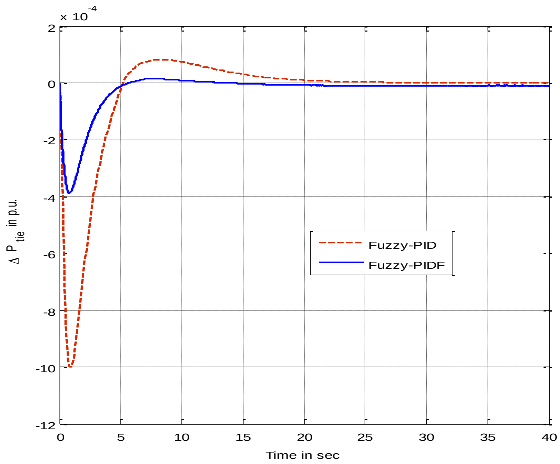

Figure 6. Oscillations of tie-line power

Table 2. The optimized constraints of fuzzy-PID and Fuzzy-PIDF controller tuned by the sin-cos algorithm

Controller Parameters	Sin-Cos algorithm tuned controller					
	Fuzzy-PIDF			Fuzzy-PID		
	Thermal	Hydro	Gas	Thermal	Hydro	Gas
F_1	2.8456	1.8975	1.3578	1.8427	0.2101	1.8754
F_2	2.7854	0.1685	2.9642	1.8978	1.0245	1.1543
F_p	2.9563	0.7523	0.8542	1.9241	0.2131	1.8763
F_i	2.3556	1.5642	1.3542	1.6214	0.6947	1.5879
F_d	2.5134	2.3564	2.6548	-	-	-
N	156.2	224.5	57.8	-	-	-

Undershoot (U_{sh}), overshoot (O_{sh}) and settling time (T_S) with 0.005 % band for Δf_1, Δf_2 and ΔP_{tie} obtained with sin-cos optimization technique for fuzzy-PID and Fuzzy-PIDF controller are shown in Table 3. Critical analysis of dynamic responses from Table 2 and Table 3 reveals that proposed sin-cos optimized fuzzy-PIDF controller holds its supremacy concerning minimum overshoot, undershoot and settling time of Δf_1, Δf_2 & ΔP_{tie}.

Table 3. Time résponse performance indices

Controllers	Δf_1			Δf_2			ΔP_{tie}		
	T_s in sec	U_{sh} in Hz (10^{-3})	O_{sh} in Hz (10^{-3})	T_s in sec	U_{sh} in Hz (10^{-3})	O_{sh} in Hz (10^{-3})	T_s in sec	U_{sh} in Hz (10^{-3})	O_{sh} in Hz (10^{-3})
FUZZY-PID	5.194	-8.6745	0.5491	2.889	-2.99	0.209	2.29	-0.955	0.0811
FUZZY-PIDF	0.987	-3.598	0.1998	1.31	-0.69	0.009	0.798	-0.29	0.0071

In the second case, random loading is subjected to area 1 to study the dynamic performance of this proposed system. It is believed that the controller is treated as efficient if it able to damp out the oscillations quickly which is caused due to the change in loading of the system. The nature of random loading is shown in Figure 7. Figure 8 represent the deviations occur in area 1 (Δf_1) due to random loading respectively. In Fig.8 the response of both Fuzzy-PID and Fuzzy-PIDF are shown simultaneously. From the Figure 8, it can be easily judged that the sin-cos tuned Fuzzy-PIDF controller exhibits superior behavior as comped to the Fuzzy-PID controller.

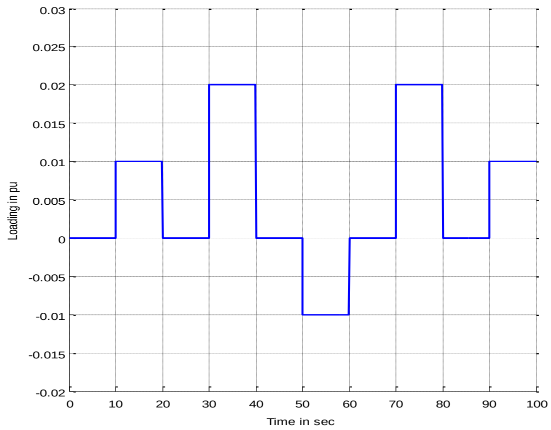

Figure 7. Nature of abnormal loading subjected to area 1

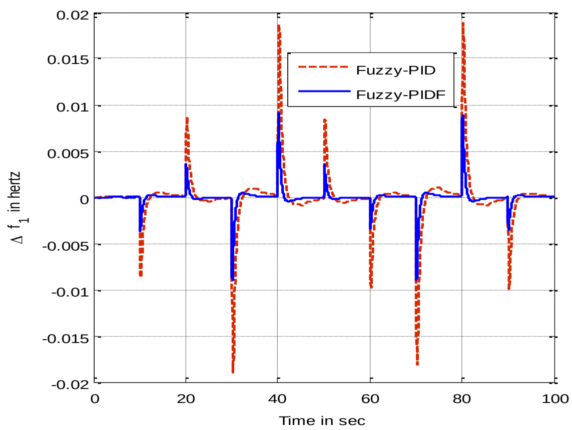

Figure 8. Oscillations of frequency in area 1 due to random disturbance

In the third case the robustness and sensitivity analysis has been carried out to prove the efficiency of sin-cos algorithm tuned Fuzzy-PIDF controller for the scrutinized two-area multi-source system as shown in Figure 1 by varying the parameters of the model like the governor speed regulation parameter (R) and frequency bias parameter (B) from -50% to +50% in steps of 25%. With the variation of the governor speed regulation parameter (R) as well as frequency bias parameter (B), the response specifications (U_{sh}, O_{sh} and T_s) are tabulated as shown in Table 4. From Table 4, it can be commented that the response indices are not varying widely even the system parameters are exposed to a wide range of deviations. Hence, it can be concluded that the system responses with sin-cos tuned suggested Fuzzy-PIDF controller is vital and perform suitably.

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

Parameters	%age deviation	$U_{sh}\times10^{-3}$ for Δf_1 (in Hz)	$O_{sh}\times10^{-3}$ for Δf_1 (in Hz)	T_s for Δf_1 (in sec)	$U_{sh}\times10^{-3}$ for Δf_2 (in Hz)	$O_{sh}\times10^{-3}$ for Δf_2 (in Hz)	T_s for Δf_2 (in sec)
R	-50%	4.3300	0.1066	-0.0012	4.9500	0.0802	-0.0002
	-25%	4.3300	0.1067	-0.0012	4.9400	0.0804	-0.0002
	+25%	4.3300	0.1069	-0.0012	4.9400	0.0806	-0.0002
	+50%	4.3300	0.1070	-0.0012	4.9400	0.0807	-0.0002
B	-25%	4.5800	0.1237	-0.0014	5.1600	0.1032	-0.0003
	-50%	4.4500	0.1141	-0.0013	5.0500	0.0907	-0.0002
	+25%	4.2200	0.1011	-0.0011	4.8200	0.0722	-0.0002
	+50%	4.1300	0.09651	-0.0010	4.7000	0.06511	-0.0002

5. CONCLUSION

In this research paper, the Fuzzy-PIDF controller was fruitfully implemented on a hybrid interconnected power system for automatic generation control. Gains of Fuzzy-PIDF controller was accurately tuned by usage of a recently published sin-cos optimization technique. Addition of UPFC and SMES boosted the dynamic performances of the modelled system. To show the robustness of suggested sin-cos algorithm based fuzzy-PIDF controller, the outputs were contrasted with sin-cos based fuzzy-PID controller. A step load perturbation of 0.01 p.u. and a sudden random loading perturbation were subjected to this suggested two area interconnected power system to check its supremacy. Further, a sensitivity analysis has been carried out by varying the governor speed regulation (R) and frequency bias parameter (B). From above analysis, discussion and simulation outputs, it can be concluded that the sin-cos optimized Fuzzy-PIDF controller in AGC system performed well against random loading perturbation and more complex engineering problems as compared to other optimization techniques.

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