Application of Fractional Order Cascaded Controller for AGC Study in Power System Integrated With Renewable Sources

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Abstract- The intent of this paper assimilates the issues of automatic generation control (AGC) of a two-area power system entailing five numbers of renewable as well as conventional sources such as thermal unit, hydro unit, wind unit, diesel unit, and photovoltaic (PV) unit. To make the proposed model more realistic, some non-linearities like boiler dynamics, governor dead band (GDB), and generation rate limit (GRC) are inducted into their concerned sources. The frequency stability of the system is enhanced by assuaging the transient indices like undershoot, overshoot, rise time, and settling time by employing two degrees of freedom (2-DOF) based fractional order (FO) cascaded controller incorporating with derivative filter (N) named 2-DOF-FOPIDN-FOPDN controller. The proposed controller along with 2-DOF-PIDN-PDN, and PID controllers are designed by endorsing selfish herd optimization technique (SHOT). The performance of the proposed controller is corroborated by comparing the performance exhibited by 2-DOF-PIDN-PDN, and PID controllers. Besides this, the know-how of the recommended controller is evaluated and investigated against solar power variation, load perturbation, and system's parameter deviation which confers the robustness of the controller is conceived.

Keywords Automatic Generation Control; Two-degrees of freedom; Fractional Cascade Controller; Selfish Herd Optimization technique.

1. Introduction

To keep abreast of a healthy, reliable, secured, and efficient power system, frequency stability is quintessential. System frequency deviates from its defined set value in the wake of normal as well as abrupt load demand. The fluctuation of frequency beyond the prescribed limit threatens to the damage of the sensing devices causing loss of stability of the system [1, 2]. In addition to this, incessant rise in size and complexity of the energy system, the system frequency, and the exchanged power between tie-lines fluctuates. In this context, the solar energy penetration causes more vulnerable to the frequency fluctuation due to its zero inertia. Apart from this, conventional sources embedding with non-linearities such as: (a) hydro unit carrying GRC, and GDB, and (b) thermal unit carrying boiler dynamics, GRC, and GDB put forth a challenge to the AGC [3]. Thus, automatic generation control is indispensable to keep the stability of the system intact by adhering the frequency, and tie-line power deviation into a subjected boundary limit [2, 4, 5].

In the current energy scenario, researchers are paying more emphasis on harvesting energy from solar, and wind renewable sources. Combination of sustainable power sources with conventional sources exhibits deviation in system frequency, terminal voltage and power transactions in tie-lines under different loading conditions. In this regard, Abd-Elazim et al. [6] analysed the stability of a two-area system integrating the PV unit by injecting variable solar power. Debnath et al. [7] innovated the integration of solar power with thermal unit to investigate the dynamic response offered by the system for AGC. Patel et al. [8] studied the influence of solar power to LFC in two-area interconnected system and demonstrated the improvement performance due to the PV unit

A well designed sophisticated secondary controller is necessary for frequency, and tie-line power stabilisation in AGC of a power system. For the last few decades, classical controllers along with its variants have been used profusely in the industries due to its simple structure which makes easier for implementation. In this perspective, PID controllers in addition to its varieties have been used in [9-13] to study the AGC issues for different kinds of power systems. With a consistent research up gradation, some researchers upped the PID structure into two stage controller named cascade controller. In cascaded controller, the signal is processed in two stages comprising of an inner loop, and an outer loop forcing the system faster to achieve the steady state. In this regard, Acharyulu et al. [14] addressed the improvement of transient response enacting a combination of PI, and PD controllers incorporating derivative filter. Das et al. [15] innovated the cascading of PD, and PID controller to ameliorate the dynamic response with that of PID controller. Tripathy et al. [16] investigated the performance produced by PD cascaded with PI controller subjecting a derivative filter in first stage. Further, the cascade controllers are reconfigured by conglomerating two degrees of freedom (2-DOF). In this controller extra scaling factor knobs help to improve the dynamic response by curtailing the transient indices as described in controller section. In this context, few papers [17, 18] illustrated the transient behaviour of power systems under the influence of 2-DOF based controller. Some researchers postulated the PID controller embedding with non-integer value of integral, and derivative operators. The functionality of this controller is described in the controller design section thoroughly. In this regard, some researchers [19, 20] studied the AGC problem to evaluate improved dynamic performance of the concerned systems.

Besides these controllers, some other kinds of controllers have been implemented in different conventional as well as restructured power systems to delve with the AGC problems such as fuzzy logic controller endorsing PID, FOPID, and cascaded integer and non-integer PID controller [11, 12, 21-23], artificial neural network based controller [24], optimal controller [25, 26] etc. These types of controllers have enough credibility to support the stabilisation of area frequency, and transacted power in tie-lines, but some drawbacks are there lying intrinsically. These are like, (a) during the enumeration of fuzzy parameters some rules are applied as discussed in [27, 28], it needs a highly matured and expertise mind to deal rather the system leads to instability, (b) in ANN, Almadhor [29] explored that for the training of the neurons it takes long time which may distract the stability of the system within a desired time, (c) In case of optimal control, Parmar et al. [30] suggested that all states in the states space model are not measureable, sensors used to extract the state variables costs more.

To reach out a better dynamic response by an accurate control signal, controllers are designed with the help of various optimisation techniques such as particle swarm optimisation technique [12, 31], symbiotic organism search algorithm [3], firefly algorithm [6, 32], bat algorithm [15], jaya algorithm [33], genetic algorithm [34], Bacteria Foraging Optimization [35] etc. From the prospective of execution time, trapping in local maxima/minima, rate of convergence to fetch a solution etc. a particular algorithm is not enough to apply in every problems which ignites the researchers mind to evolve new algorithms.

Despite the fact that the established fractional order control strategies with/without 2-DOF for AGC have worked significantly, still new control structure is expected to design by which the system response can be ameliorated further. So in this perspective a 2-DOF fractional order cascade controller is configured, and designed with the help of SHOT algorithm [36] subjecting to an ITAE cost function. The main contribution of this paper is quoted below:

a. A test model of two-area multi-source power system consisting of five different conventional as well as renewable energy sources is simulated in the MATLAB/Simulink environment aided by GRC, GDB and boiler dynamics non-linearities to their concerned sources.

b. A novel 2-DOF-FOPIDN-FOPDN controller is used to ameliorate the transient response of the proposed model.

c. SHOT algorithm is endorsed for the first time to design the controller assisted by ITAE cost function.

d. Comparative analysis of results produced by PID, 2-DOF-PIDN-PDN, and 2-DOF-FOPIDN-FOPDN controllers is illustrated against 1% step load change injecting in area-1.

e. Robustness of the designed controller is examined by imposing random step load variation, solar power variation, random step load along with solar power variation, and parameter variation

2. Linearised Model of the investigated system

The recommended model is presented in "Fig. 1" which is composed of five different renewable as well as conventional sources deployed in two areas. In the first area, with the hydro-thermal system a PV unit along with wind power system is connected. In second area, the wind unit is replaced by a diesel unit keeping other sources as in area-1. Mathematical modelling of hydro-thermal unit, diesel unit, wind farm, and GDB for hydro unit expressed in frequency domain along with their source capacity, and parameters are taken from Guha et al. [3]. Linearised model for GRC of hydro (GRC_h), GRC for thermal (GRC_t), and GDB for thermal unit with their required data are referred from Morsali et al. [37]. The GRC for thermal unit is taken as 10%/min in both rising, and falling of generation. Similarly, for hydro unit the GRC is maintained by a rate of 270%/min during rising, and 360%/min during falling. The GRC for these two units are given in "Fig. 2(a)". Another constraint in thermal system aroused due to the excessive pressured incurred to the flow of fuel, and steam in a drum type boiler is depicted in "Fig. 2(b)". The boiler dynamics in frequency domain besides its parameters for thermal units are taken from [38]. The backlash of GDB is taken as 0.06% from [37] with the Fourier constants, $N_1 = 0.8$, and $N_2 = -0.2$ inherited from [3, 37, 38]. The PV unit model is referred from Gaur et al. [39] with required data. The parameters of all the sources, and non-linearities are presented in the appendix.

3. The proposed 2-DOF-FOPIDN-FOPDN Controller

The proportional-integral-differential (PID) controller is used profusely in the industries due to its simple structure. It is composed of three operators such as proportional (P), integral (I), and differential (D). The control signal (u_i) is expressed in "Eq. (1)".

$$u_{PID_i} = k_{p_i}\, e(t) + k_{i_i} \int e(t)\, dt + k_{d_i} \frac{d}{dt}\big(e(t)\big) \tag{1}$$

Where, k_{p_i}, k_{i_i}, and k_{d_i} are proportional, integral, and differential gains respectively.

The PID controller shows miserable transient performance against non-linearities, parameter variation, and even to higher order systems. To achieve an improved transient profile, the integer order operators of integral, and differential terms are incapable. So researchers are paying their efforts to restructure the PID controller by subjecting non-integer operators. The feasibility, and reliability of fractional order PID (FOPID) controller are well understood from "Fig. 3(a)". "Figure 3(a)" describes that the PID controller works at definite co-ordinates like (0,0), (0,1), (1,0), (1,1). But FOPID controller as illustrated by Podlubny [40] works over the whole surface of the first quadrant by which it is flexible to improve the dynamic performance by reducing overshoot/undershoot/rise time. The control structure of FOPID is shown in "Fig. 3(b)", and its control signal in frequency domain is given in "Eq. (2)".

$$u_{FOPID_i}(s) = k_{p_i} + \frac{k_{i_i}}{s^{\psi}} + k_{d_i} s^{\zeta} \tag{2}$$

Where, $\psi, and\ \zeta$ are the integral, and differential fractional operator respectively.

But, with the consistent research work, the PID structure is evolved by two stage PID controller. In this controller, the control signal is processed in two stages named as inner loop control signal, and outer loop control signal. The inner loop control signal is faster by which the system dynamics is accelerated produce a faster response. The control structure of cascaded controller is depicted in "Fig. 3(c)". The control signal of the cascade controller is given in "Eq. (3)".

$$Y(s) = \left(\frac{g_1(s).g_2(s).c_p(s).c_s(s)}{1 + g_2(s).c_s(s) + g_1(s).g_2(s).c_s(s).c_s(s)} \right).r(s) + \left(\frac{g_1(s)}{1 + g_2(s).c_s(s) + g_1(s).g_2(s).c_p(s).c_s(s)} \right).d_1(s) \tag{3}$$

Where, $g_1(s)$, $g_2(s)$ are plant transfer functions, and $c_p(s)$, $c_s(s)$ are the transfer functions of primary controller (2-DOF-FOPIDN), and secondary controller (2-DOF-FOPDN) respectively. And, d_1 is the disturbance signal, and $r(s)$ is the area control error signal.

In this paper, to fasten an ameliorate performance, the cascade controller is configured by fractional order operator incorporating two degrees of freedom technique to produce a 2-DOF-FOPIDN-FOPDN controller. The structure of proposed 2-DOF-FOPIDN-FOPDN controller is portrayed in "Fig. 3(d)". "Figure 3(d)" shows that in the inner loop, 2-DOF-FOPD controller is assisted by a derivative filter (N) to mitigate the noise produced by any sensors through the feedback path. And in the outer loop, the 2-DOF-FOPID controller with derivative filter is present. The control signal of 2-DOF-FOPIDN-FOPDN controller is derived by the following equations.

The transfer function, $G_1(s)$, and $G_2(s)$ of $PI^{\psi} D^{\zeta} N$, and $PD^{\zeta} N$ controllers are given in "Eq. (4)" and "Eq. (5)" respectively.

$$G_1(s) = k_{p_i} + \frac{k_{i_i}}{s^{\psi}} + k_{d_i} s^{\zeta} \left(\frac{N}{N + s^{\zeta}} \right) \tag{4}$$

$$G_1(s) = k_{p_i} + k_{d_i} s^{\zeta} \left(\frac{N}{N + s^{\zeta}} \right) \tag{5}$$

And the control signal $U(s)$ after two stages is evaluated by "Eq. (6)". Here, $Y(s)$ is the output signal (Δf).

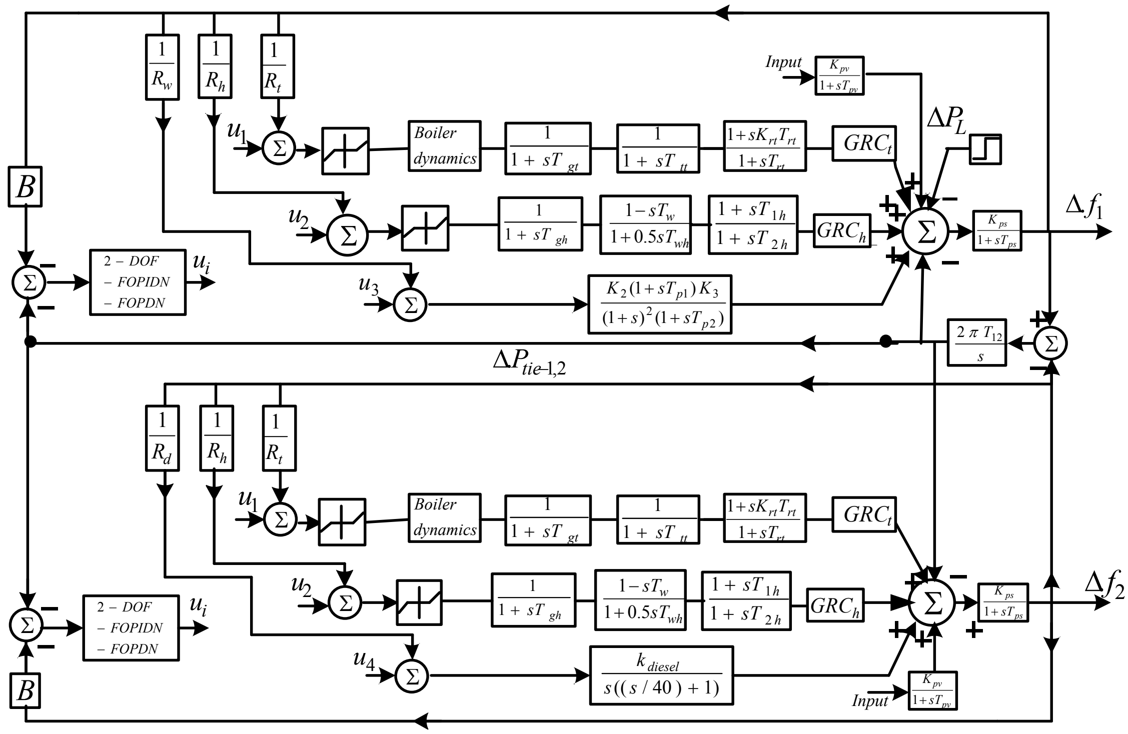
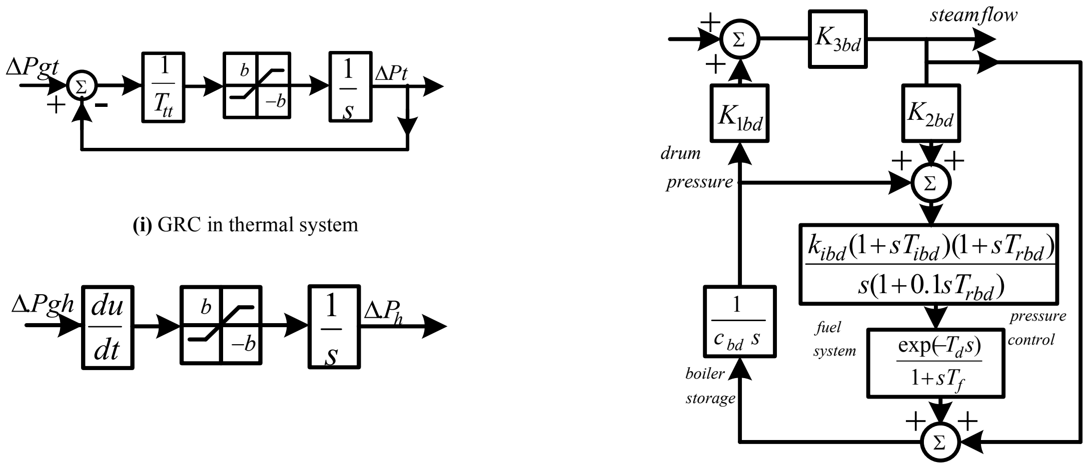


Fig. 1. Model of the two-area power system containing renewable sources.



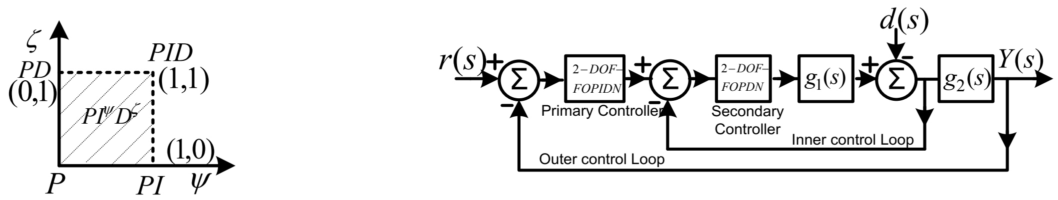
(i) GRC in thermal system

(ii) GRC in Hydro system

(a)

(b) Boiler dynamics model

Fig. 2. (a) GRC for thermal, and hydro system, **(b)** boiler dynamics for thermal system.



(a)

(c)

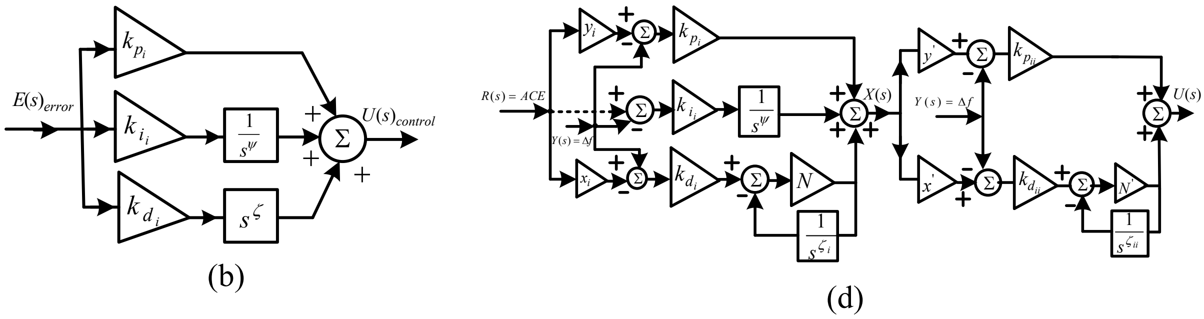


Fig. 3. (a) Working co-ordinate of PI, and FOPID controller, **(b)** structure of FOPID controller, **(c)** structure of cascade controller, **(d)** structure of 2-DOF-FOPIDN-FOPDN controller.

$$U(s)=\begin{bmatrix}\left\{xk_{p_i}+k_{i_i}s^{-\psi}+yk_{d_i}s^{\varsigma}\left(\dfrac{N}{N+s^{\varsigma}}\right)\right\}\\ \times\left\{x'k_{p_i}+y'k_{d_i}s^{\varsigma}\left(\dfrac{N}{N+s^{\varsigma}}\right)\right\}\end{bmatrix}R(s)-\begin{bmatrix}\left\{k_{p_i}+k_{i_i}s^{-\psi}+k_{d_i}s^{\varsigma}\left(\dfrac{N}{N+s^{\varsigma}}\right)\right\}\\ \times\left\{k_{p_i}+k_{d_i}s^{\varsigma}\left(\dfrac{N}{N+s^{\varsigma}}\right)\right\}\end{bmatrix}Y(s) \quad (6)$$

4. Mathematical problem formulation

The two-region control based power system model portrayed in "Fig. 1" is investigated by using three different controllers such as PID, 2-DOF-PIDN-PDN, and 2-DOF-FOPIDN-FOPDN controller. The weight bias factors along with gains of controllers are evaluated endorsing a recently developed SHOT algorithm. To study the systems stability, a load change of 1% is injected in area-1. To ameliorate the system's dynamics cost function ($J_{\cos t}$) value is curtailed during the optimization of controller's gains. Here, the cost function is considered as minimization problem incorporating a fitness function, integral time absolute error (ITAE). The cost function is expressed in "Eq. (7)".

$$J_{\cos t}=\int_0^T\left[\left|\Delta f_1\right|+\left|\Delta f_2\right|+\left|\Delta p_{tie-1,2}\right|\right].dt \quad (7)$$

In order to determine the optimal controllers' gains, the objective function 'J' is minimized subjecting to the following constraints:

$$k_{p,min}\le k_p\le k_{p,max},\ k_{i,min}\le k_i\le k_{i,max},$$
$$k_{d,min}\le k_d\le k_{d,max},\ \ N_{min}\le N\le N_{max}.$$

Where, $k_{pid,\min}$ and $k_{pid,\max}$ are taken in between 0.01 and 5, and the filter coefficients (N) are taken in between 20 and 200. Besides this, the weighting parameters of 2-DOF cascaded controller x_i, x'_i, y_i, and y'_i are taken in the interval of (0,1).

5. Selfish Herd Optimization Technique (SHOT)

Dates back to 1971 Hamilton recommended a theory based on Selfish Herd. Fausto et al. [36] emulated this theory further to an optimization algorithm named SHO. The theory deals with the behavioral characteristics of the herd divided into two groups like Herd and Predator. The principle behind each individual is to survive from the predators by changing its' position. The individual conceding higher survival value vows the safest position and vice versa. But the predator individuals change their positions to attack and kill the herd. Predator can kill the herd if the herd is within its' domain of danger and survival value of the predator is more than that of herd. The complete architecture of the algorithm is described in the flowchart as cited in "Fig. (4)" and the pseudo code depicted below:

Pseudo code for SHOT

Inputs: Number of population (NP), maximum no iteration (itermax), Upper limit (X_{jhigh}), Lower limit (X_{jlow}), dimensions of the problem (D).

Step-1: Initialization

Randomly create the initial population (prey).

Step-2: Classification of prey

Divide the preys into two groups namely Herd and Predator and evaluate their survival.

Step-5: Updation the positions of herd and predators.

Update the position of herd and predators and evaluate their performance.

Step-7: Re-evaluation of fitness function

Evaluate the fitness of updated herd and predator.

Step-8: Predation phase

Determine the domain of danger's radius.
Determine the members of threatened group.
Determine the probability of being hunted.

Step-9: Restoration phase

Define a set of mating candidates.
Evaluate the mating probability.
Update the herd members.

Step-10: If the termination criteria are not met go to step 2.

6. Result Analysis

The linearised model of the proposed two-area system involving non-linearities is simulated in the environment of MATLAB/Simulink. To stabilise the system, three different secondary controllers for AGC such as PID, 2-DOF-PIDN-PDN, 2-DOF-FOPIDN-FOPDN are used separately. The controllers are designed by endorsing SHOT algorithm which is subjected to a minimisation problem (minimum area control error) incorporating ITAE cost function. The controller's gains are assembled in "Table 1.".

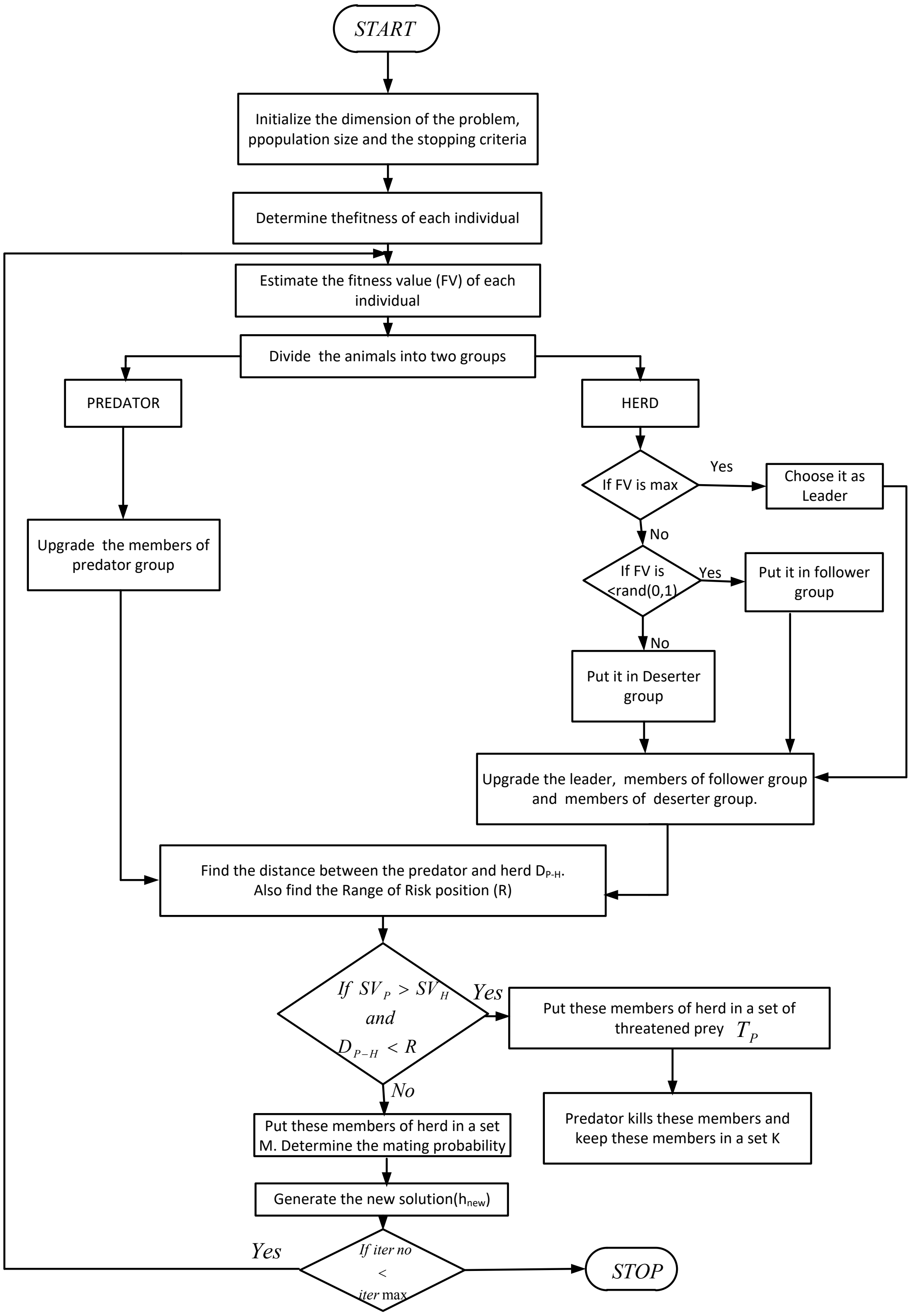


Fig. 4. Architecture/Flowchart of SHOT.

The dynamic response of the system as well as the potential of proposed 2-DOF-FOPIDN-FOPDN controller is evaluated by subjecting different test conditions like (a) keeping PV power constant, and injecting 1% load in the first area by step function, (b) varying PV power and injecting same amount of load in the first area, (c) varying both PV power, and injected load in first area, (d) varying only load randomly, keeping PV power constant, (e) varying parameters of the power system.

Case-1: Keeping PV power constant, and injecting 1% load in the first area by step function.

In this case, the harness of solar power is set at 0.2 pu. A 1% load is injected in the first area, and the transient response of the system is evaluated distinctly by subjecting three controllers. “Figure 5” shows the frequency excursion of two areas along with tie-line power. In area-1, the frequency response produced by the 2-DOF-FOPIDN-

FOPDN controller is showing minimal overshoot, low rise time, and low time constant. But, the response observed by PID, and 2-DOF-PIDN-PDN controllers is sluggish, producing high peak overshoot. Similarly, the peak values of overshoots of frequency in second area, and tie-line power curve have diminished sharply by the proposed 2-DOF-FOPIDN-FOPDN controller in comparison to PID, and 2-DOF-PIDN-PDN controllers. The quantized transient indices of area control error are amassed in "Table 2.". The analysis of data given in "Table 2." brings a close attention that overshoot of Δf_1 due to 2-DOF-FOPIDN-FOPDN controller reduced by 99.1627 %, 98.5184 % that of PID, and 2-DOF-PIDN-PDN controller respectively. Similarly, peak value of Δf_2 truncated by 99.9540 %, and 99.8989 % that of PID, and 2-DOF-PIDN-PDN controller respectively. And $\Delta P_{tie-1,2}$ overshoot has assuaged by 99.8445 %, 99.7953 % that of PID, and 2-DOF-PIDN-PDN controller respectively.

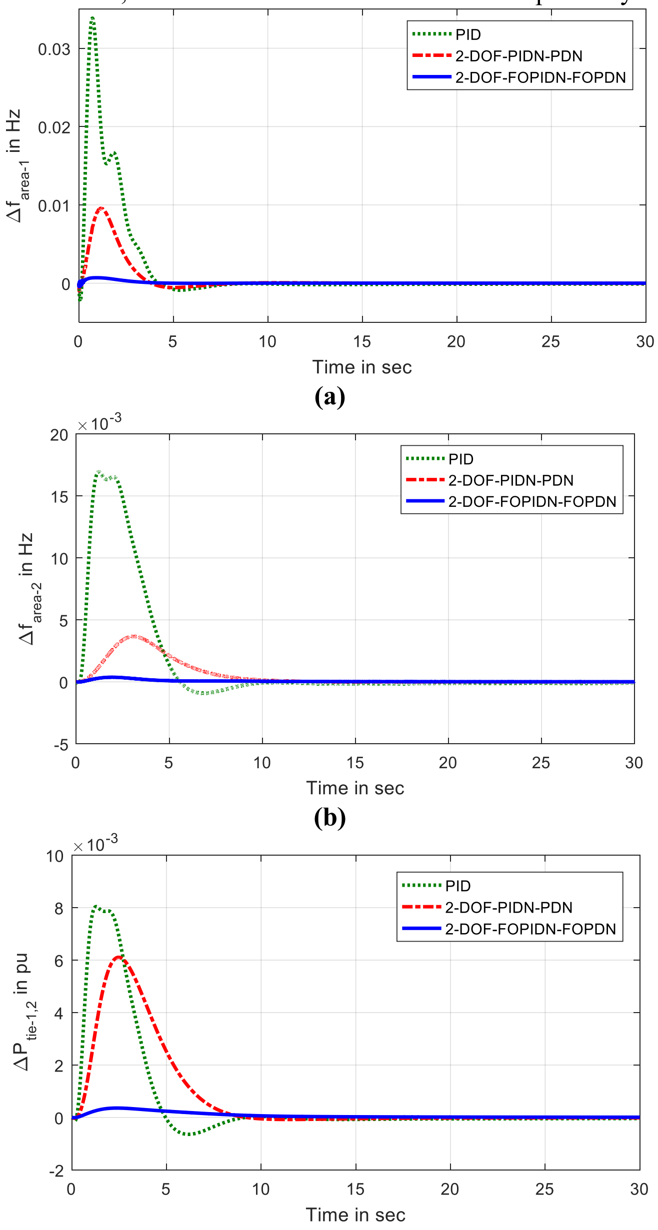


Fig. 5. **(a)** Frequency deviation in area-1, **(b)** frequency deviation in area-2, **(c)** power deviation in the tie-line.

Case-2: Varying PV power and injecting same amount of load in the first area

Under this scenario, variable solar power produced by sporadic solar insolation is injected in both areas. The dynamic behaviour of the system is studied by applying the 2-DOF-FOPIDN-FOPDN controller keeping its gains constant which are used in case-1. The excursion of frequency in area-1, and tie-line power gets smoothed due to more amount of solar power injected into the system. Because, the power deficit due to more demand is compensated by the solar power. The time diagram of solar power variation, first area frequency deviation, and tie-line power deviation portrayed in "Fig. 6" shows that the intricacy ought to be produced by PV system due to its zero inertia is seldom observed, and mitigated by the proposed 2-DOF-FOPIDN-FOPDN controller designed by SHOT algorithm for AGC.

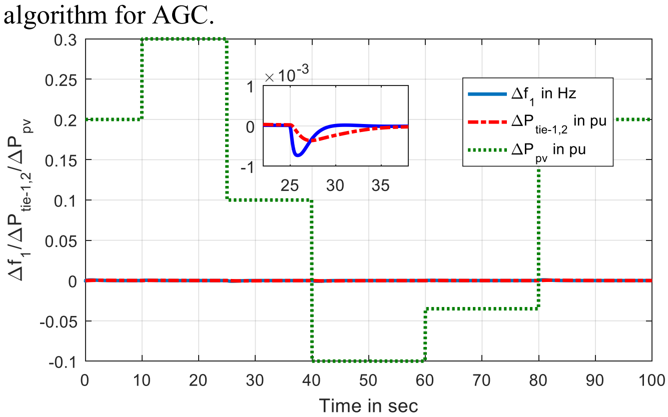


Fig. 6. Time diagram of solar power variation, frequency deviation, and tie-line power deviation.

Case-3: Varying both PV power, and injected load in the first area.

Here, variable solar power is injected in both areas, and a random load perturbation in step are subjected to employing the proposed 2-DOF-FOPIDN-FOPDN controller. The dynamic response of first area frequency, and tie-line power shown in "Fig. 7". The transient effect has not pronounced, although both load, and solar power variation is subjected. Fact that the more deficit power is compensated by the solar power i.e. the difference between solar power, and demand is narrowed, and due to the 2-DOF-FOPIDN-FOPDN secondary controller of AGC, the frequency stabilization of the system remains intact furnishing a meagre change in undershoot without affecting the settling time. For this, the design of 2-DOF-FOPIDN-FOPDN controller with the help of SHOT algorithm pays a key role which is to be advocated from the performance observed as in "Fig. 7".

Table 1. Gain parameters of controllers.

Controller with gains		Controller-1	Controller-2	Controller-3	Controller-4
PID	k_{p_i}	2.5000	1.9619	2.5000	2.5000
	k_{i_i}	2.5000	1.8074	2.5000	2.5000
	k_{d_i}	2.5000	2.5000	2.4003	1.1651
2-DOF-PIDN-PDN	k_{p_i}	2.0913	1.5434	1.9912	0.7411
	k_{i_i}	0.4199	0.3921	2.6812	1.7460
	k_{d_i}	0.7101	1.1788	1.2595	0.8287
	$k_{p_{ii}}$	2.4745	1.2852	1.0891	0.8900
	$k_{d_{ii}}$	2.0578	2.3797	1.3946	0.9810
	x_i	0.8797	0.6269	0.3047	0.0228
	y_i	0.4214	0.6726	0.3235	0.1790
	x'_i	0.9071	0.3443	0.8047	0.3703
	y'_i	0.1278	0.8442	0.6946	0.8904
	N	29.1389	120.4444	27.9066	144.4060
	N'	125.1343	140.3932	118.3123	107.3879
2-DOF-FOPIDN-FOPDN	k_{p_i}	3.5000	1.7363	3.0159	1.3746
	k_{i_i}	2.9831	3.0798	3.5000	3.5000
	k_{d_i}	3.5000	2.8730	2.8830	3.2120
	$k_{p_{ii}}$	2.3745	3.5000	3.5000	3.4195
	$k_{d_{ii}}$	1.9486	3.3748	1.2456	3.4074
	x_i	2.1250	1.4949	1.7208	2.5000
	y_i	0.4848	2.5000	0.6227	2.5000
	x'_i	2.5000	1.7581	2.5000	2.5000
	y'_i	1.7808	2.5000	2.5000	1.0440
	N	63.2806	31.9564	90.3519	44.2381
	N'	126.7574	129.0140	59.7216	78.5043
	ψ	0.6957	0.8530	0.9000	0.9000
	ζ_i	0.9000	0.9000	0.9000	0.9000
	ζ_{i_i}	0.9000	0.9000	0.9000	0.9000

Table 2. Transient parameters of frequency, and tie-line power deviation.

	PID			2-DOF-PIDN-PDN			2-DOF-FOPIDN-FOPDN		
Indices	Δf_1	Δf_2	ΔP_{tie}	Δf_1	Δf_2	ΔP_{tie}	Δf_1	Δf_2	ΔP_{tie}
$o_{sh} \times 10^{-3}$	16.935	8.0377	8.0377	9.5706	3.6592	6.1052	0.1418	0.0037	0.0125
$u_{sh} \times 10^{-3}$	-2.3374	-0.9167	-2.3374	-1.0459	-0.0247	-0.0754	-0.5158	-0.0345	-0.0413
t_s in sec	3.623	14.200	10.960	2.827	9.434	9.110	1.108	0.945	5.237

Table 3. Transient parameters of frequency, and tie-line power deviation subjecting to parameter variation.

Parameters	Variation in %	Δf_1			Δf_2			Δf_3		
		u_{sh} in mHz	o_{sh} in mHz	t_s in sec	u_{sh} in mHz	o_{sh} in mHz	t_s in sec	u_{sh} in mHz	o_{sh} in mHz	t_s in sec
T_w	-20	-1.0488	9.5724	7.0379	-0.0092	3.6604	9.3484	-0.0755	6.1063	8.0414
	+20	-1.0439	9.5693	7.0398	-0.0094	3.6597	9.3495	-0.0755	6.1063	8.0431
K_r	-20	-1.0412	9.5443	6.9865	-0.0099	3.6999	9.3076	-0.0762	6.2190	7.9879
	+20	-1.0507	9.6131	7.0814	-0.0088	3.6210	9.3936	-0.0749	5.9917	8.0966
T_t	-20	-1.0517	9.4799	7.0546	-0.0093	3.6435	9.3432	-0.0757	6.0627	8.0340
	+20	-1.0420	9.6167	7.0202	-0.0096	3.6756	9.3532	-0.0754	6.1522	8.0503
K_{ps}	-20	-0.8795	9.6013	7.0204	-0.0094	3.6818	9.3472	-0.0755	6.1518	8.0331
	+20	-1.2098	9.7321	7.0543	-0.0094	3.6403	9.3504	-0.0752	6.0686	8.0509
T_{ps}	-20	-1.2503	9.8744	7.0420	-0.0094	3.6348	9.3486	-0.0752	6.0584	8.0531
	+20	-0.9074	9.5957	7.0227	-0.0095	3.6785	9.3473	-0.0755	6.1441	8.0340
B	-20	-1.0456	9.8155	6.7747	-0.0092	3.9196	9.3413	-0.0928	6.3132	7.7124
	+20	-1.0464	9.3407	7.3018	-0.0095	3.4257	9.3685	-0.0626	5.9115	8.3671
R	-20	-1.0459	9.5142	7.1202	-0.0087	3.5614	9.5423	-0.1022	6.0700	8.0239
	+20	-1.0459	9.6084	6.9849	-0.0099	3.7271	9.2183	-0.0586	6.1292	8.0665
Standard Deviation		0.0942	0.1339	0.1090	0.0003	0.1045	0.0669	0.0106	0.0959	0.1306

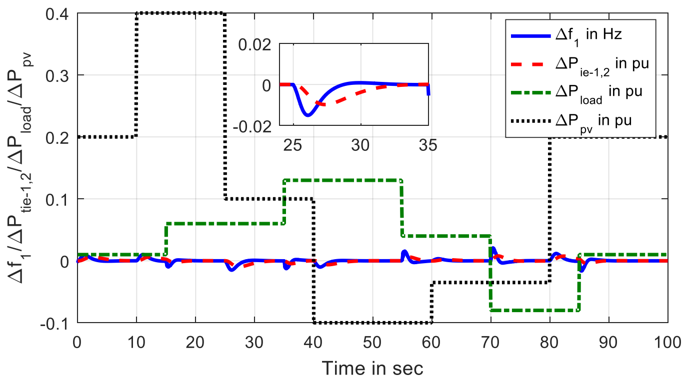


Fig. 7. Time diagram of solar power variation load variation, frequency deviation, and tie-line power deviation.

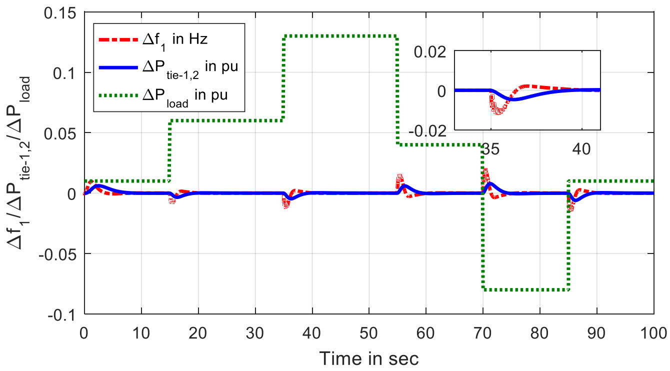


Fig. 8. Time diagram of load variation, frequency deviation, and tie-line power deviation.

Case-4: Varying only load randomly, keeping PV power constant.

In this condition, a random load of high magnitude expressed in step function is injected in the first area, keeping the solar power constant of 0.2 pu. With the enactment of this highly magnified load perturbation, the power disparity between demand, and generation of the system increases. In spite of this large power deviation, the steady state of frequency, and tie-line power deviation is perceived promptly. In “Fig. 8”, the area control error signals are exhibiting less undershoot along with a minimum settling time. The zoomed portion of the dynamic response elucidates that the stability of the system under proposed 2-DOF-FOPIDN-FOPDN controller is achieved adequately.

Case-5: Varying parameters of the power system.

In this context, the impact of parameter variation to the controller, hence to the performance to the system is analyzed. Some crucial parameters of the proposed test system such as reheat gain (K_r), water time constant (T_w), turbine time constant (T_t) of thermal unit, control area gain (K_{ps}), control area time constant (T_{ps}), frequency bias constant (B), speed regulation constant (R) are varied by $\pm 20\%$ keeping a load of 1% in the first area. The sensitivity, circuitously the capability of the proposed 2-DOF-FOPIDN-FOPDN controller is ascertained by evaluating the standard deviation. The transient indices of frequency, and tie-line power deviation curves are presented in “Table 3.”. The standard deviation confers the efficacy of the 2-DOF-

FOPIDN-FOPDN controller designed by SHOT algorithm employed for AGC in the intricacy power system.

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7. Conclusion

In this paper, a maiden attempt is taken to recommend a 2-DOF-FOPIDN-FOPDN controller as a secondary controller in AGC of a two-area power system in the presence of renewable sources as well as in the presence of GRC, GDB, and boiler dynamics non-linearities to stabilize the frequency along with power transaction in the tie-lines. The proposed controller is designed by a recently reported SHOT algorithm substantially ameliorates the transient profile of frequency, and tie-line power deviation in comparison to 2DOF-PIDN-PDN, and PID controllers. In addition to this, the 2-DOF-FOPIDN-FOPDN controller with the same designed gain parameters supports superbly to random load perturbation, solar power variation, and $\pm 20\%$ of nominal values of system parameters which deliberates the robustness of the controller is to be perceived.

Appendix

Parameters of the proposed work

Symbol	Parameters	Values used in this work [27]
T_{gt}	Governor time constant of thermal system	0.2sec
T_{tt}	Turbine time constant of thermal system	0.3 sec
T_{rt}	Re-heat time constant	10.0 sec
K_{rt}	Re-heat gain	0.333
T_{PS}	Control area time constant	20 sec
K_{PS}	Control area gain	120
R	Regulation constant	2.4 Hz/MW
B	Frequency bias constant	0.425 MW/Hz
T_{12}	Synchronization coefficient	0.0707
K_2	Wind turbine generator gain	1.25
K_3	Wind turbine generator gain	1.4
T_{p1}	Wind turbine generator time constant	0.6sec
T_{p2}	Wind turbine generator time constant	0.041sec
T_{gh}	Governor time constant of hydro system	48.7sec
T_{1h}	Hydro turbine time constant	0.5 31sec
T_{2h}	Hydro turbine time constant	10sec
T_{wh}	Water reheat time constant	1 sec
K_{diese}	Gain of diesel engine generator	16.5
K_{pv}	Gain of solar system	1
T_{pv}	Time constant of solar system	1.8 sec
T_{ps}	Control area time constant	20 sec

Boiler Dynamics:

$K_{1bd} = 0.85$,

$K_{2bd} = 0.095$, $K_{3bd} = 0.92$, $c_{bd} = 200$,

$K_{ibd} = 0.03$, $T_{ibd} = 26\,s$, $T_{rbd} = 69\,s$, $T_d = 0$, $T_f = 10\,s$.

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