Application of EV aggregators and SMES for frequency deviation control using fractional fuzzy controller

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ABSTRACT

Secondary controllers are implemented in the alternator control loop to take care of the swinging of frequency initiated due to inequality of load and demand. A fractional fuzzy-PID controller (FFPID) is projected in this work for frequency deviation control in unified system including EV aggregators and superconducting magnetic energy storage (SMES). EVs and SMES are given primacy because of their ecofriendly nature. Proper adjustment of gains of FFPID is also required to extract the best performance of the secondary controllers. Here a recent tuning process named as artificial rabbits optimization (ARO) is applied for proper tuning of projected controller. The implemented dual area power system includes time varying delay-based EV aggregators, SMES, and thermal generating units. The ARO technique is applied in the model to tune the controller constraints with abrupt increment of demand in one of the control areas. A time-based function is treated as fitness function to evaluate the system performance. The dominance property of the projected FFPID controller over conventional PID and FPID controller in terms of different response specifications like maximum positive deviation (overshoot), settling time and minimum negative deviation (undershoot). The robust nature of the projected controller is also confirmed by multiple analysis like random load deviations and system constraint alteration.

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1. INTRODUCTION

Generator control loops take care of the active and reactive power generation of the system. Thereby it controls frequency and terminal voltage of the alternator [1]. Load frequency control (LFC) acts along with speed governor to regulate the deviations of frequency occurred due to imbalance between demand and generation [2]. It's the duty of LFC to decay the oscillations of frequency and interline power of the unified system within a tolerable band due to uncertain demand variations. The reliable and stable operation of the unified power network mainly depends on the well-functioning of the LFC loop. The loss of stability due to uncertain load perturbations may results in the loss of synchronization of the alternators.

LFC loop must cope up with the increasing demand of the load in the unified power network. The secondary controllers have used by many researchers in the alternator control loop to accelerate the control action of the LFC loop. Initially traditional simple controllers [3] were implemented by the researchers to enhance the alternator control loop. The increase in demand for bulk power having a proper increased reliability was established. Power system stability is an issue that can establish a state of operating equilibrium after the occurrence of the disturbance with bounded system constraints. The disruption stated in the above could be by the load changes, fault, line outages, generator outages, voltage collapse or few combinations of these. The severe disturbances in power system produce large power swings. If this phenomenon continues for a long time, the faulted portion of the power system network/component is isolated from the remaining healthy system with the help of circuit breakers to prevent further additional damage. Isolation interrupts the continuity of power supply to the faulted section of the power system. In order to achieve stability different modes of condition is achieved like rotor angle, voltage and frequency stability. Numerous stochastic search techniques to set the gain parameters of the PID controller are explained in [4]. A decentralized control parameter to achieve an operating point in a three area power system is evaluated in [5]. Sensitive performance analysis for system parameter and operating load condition is explained in [6]. Schedule interchanging of distributed approach to modify the conventional AGC is done in [7]. Fuzzy and neural network approach to the AGC based on hydrothermal system is explained in [8], [9]. A droop control microgrid with DSC control is explained in [10]. An optimized hybrid fuzzy PID controller with LUS-TLBO algorithm is explained in [11], [12]. FOPI-FOPD based energy storage devices in deregulated AGC are explained in [13]. Frequency regulated based PID-fuzzy-PID two area network is proposed in [14]. Stability criterion analysis with delay constraints in the LFC based system is explained in [15], [16]. Meta heuristic approach on bio inspired optimization issues are explained in [17], [18]. Modified TID controller with interconnected diverse unit power system is elaborated in [19]. Deregulated power system with brain emotional based intelligent controller is explained in [20]. To compensate the increasing demand, renewable sources integrated microgrids [21], [22] were examined by the researchers for frequency deviation control. Communication delay was considered in article [23] along with EV aggregator for observing control of frequency oscillations. Leader Harris Hawks technique was employed in paper [24] for LFC observation in unified network. Arya [25] implemented FTIλDN controller for damping the oscillations of response in the thermal based unified network.

From the above survey it can be observed that many research articles have incorporated different control techniques for effective control of frequency deviations in multi-area unified power system. In this research paper fractional calculus is used along with fuzzy controller to develop fractional fuzzy controller for frequency deviation regulation of unified power network. The following points highlighted the key contributions of the paper:

- Application of EV aggregators, SMES along with thermal units in unified network for examining frequency deviation control.
- Use of fractional calculus to model fractional fuzzy-PID (FFPID) controller.
- Augment the recommended controllers with the efficient artificial rabbits optimization technique.
- Endorsing the ascendency of stated FFPID controller over FPID and PID controller in view of different response specifications like maximum positive deviation (overshoot), settling time and minimum negative deviation (undershoot).
- Evidencing the robustness of implemented FFPID controller by applying arbitrary demand variations and system constraint deviations.

2. SYSTEM EXAMINED

Frequency deviation control analysis is become essential with the application of EV aggregators. A large number of EVs are accounted as EV aggregators and employed along with other generating sources in multi-area system for frequency deviation control. The time delay of EV aggregators may result in the delay of system response because of which the stability of the system may be affected. In this research analysis a dual-area system is examined where EV aggregators are employed along with thermal generating power units in each area. Governor dead band (GDB) and generation rate constraints (GRC) are also considered along with each thermal unit to make the system more practical. The examined model includes GRC of 3%/min for each thermal unit. For the GDB, 0.036 is considered as limiting value. The transfer function-based model of the examined dual-area unified power system is illustrated in Figure 1. The nominal parameters of the model are considered from article [14] and are detailed in the Table 1. The simplified transfer function of the EV aggregators [14] is presented by (1).

$$G_{EV}(s) = \frac{K_{EV}}{1+sT_{EV}} \tag{1}$$

Where the EV gain is denoted by KEV and TEV is the battery-based time co-efficient of the EV. For the EV aggregators the time varying delay is accounted by a sine wave function [14] with bias and amplitude taken as 1. For the scrutinized system the time varying delay is taken in the range [0.5 s].

An SMES unit [6] is installed in each control area which has the ability to normalize the real power of the unified system. The transfer function of the SMES unit is depicted in Figure 1. In the Figure 1, α1, and α2 are the participation factors for each generating unit of the dual-control area system. Two FFPID controllers are applied for smooth control of frequency in the designed unified model. The rated values of the system constraints are delivered in the Table 1.

Table 1. Nominal values of the constraints of the scrutinized model

Parameters	Values	Parameters	Values	Parameters	Values
M	8.8	Fp	1/6	α_2	0.4
Tg	0.2	Tev	0.1	α_1	0.6
Tr	12	Kev	1	T_{12}	2
Tc	0.3	B	21	T_{SMES}	0.035l
D	1	R	1/11	K_{SMES}	0.12

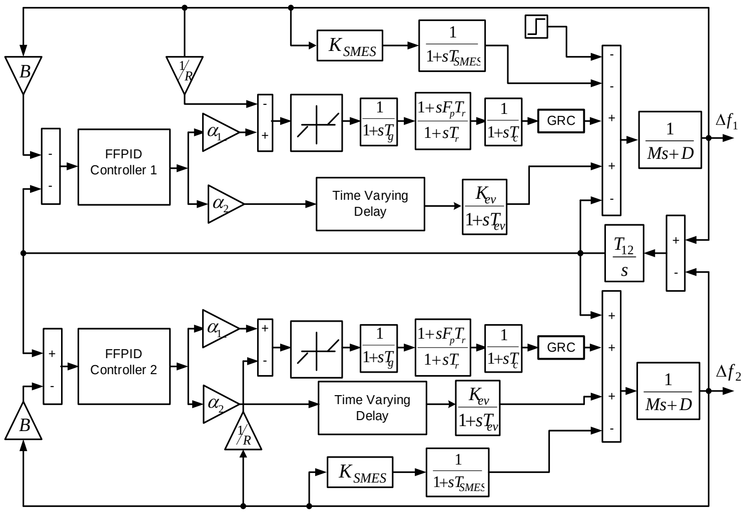

Figure 1. Power system integrated with EV and SMES represented by transfer function

3. METHODOLOGY

3.1. Artificial rabbits optimization (ARO)

ARO is an effective and modern tuning algorithm projected by Wang *et al* [18]. The entire process of ARO is centered on the survival behavior of rabbits in the environment. This tuning process basically based on two behaviors of the rabbits namely, random hiding and detour foraging. The detour foraging approach of rabbits applies them to eat food near the nests of other rabbits, by this their nest can't be discovered by the predators. Random hiding behavior of rabbits allows them to choose a burrow arbitrarily for hiding, by this they can avoid the enemies from being captured. The various steps involved in ARO algorithm is as follows:

a) Initialize the position of rabbits ($C_{p1}\ C_{p2}\ C_d\ C_i\ \lambda\ \mu$) and all other controlling factors. As there are two controllers, total number of controller's parameters is 12.
b) Compute the energy coefficient A.
c) For A>1 select a random rabbit and execute detour foraging.
d) For A<1 choose a random burrow for hiding and execute arbitrary hiding.
e) Use fitness function in (2) to evaluate rabbits and update their positions.
f) Based on fitness update the fittest solution.
g) Check the termination criteria of the algorithm, if met stop and return the finest solution, else go to step b. The finest solution represents the optimum controller's gain.

The details of the algorithm can be found in the article [18].

3.2. FFPID controller architecture

The traditional fuzzy-PID controller consists of integer order PID controller with a fuzzy inference system. This means that the values of two tuning variables attached to the integral and derivative controller should have unity value i.e, $\lambda = \mu = 1$. In a fractional calculus based fuzzy PID controller, the integral and derivative controllers come with two adjustable parameters λ and μ and can have any values between 0 and 1. Keeping aside the stated differences, all other design aspects of a FFPID controller is exactly the identical as the traditional integer order fuzzy-PID controller. Fuzzy-PID controller can be said to be a special case of FFPID when $\lambda = \mu = 1$. Figure 2 illustrates the structure of FFPID controller. The membership functions and rule-base of FFPID controller are depicted in Figure 3 and Table 2 respectively.

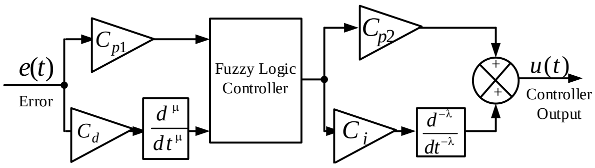

Figure 2. Internal design of FFPID controller

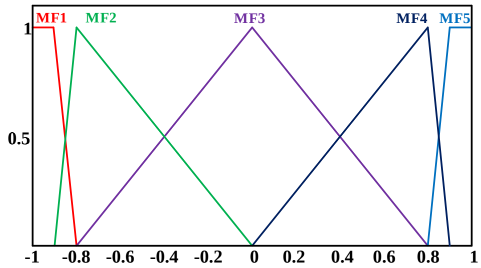

Figure 3. Membership function structure of FFPID controller

Table 2. Twenty-five rules of fuzzy structure of FFPID controller

Error	Δerror				
	MF1	MF2	MF3	MF4	MF5
MF1	MF1	MF1	MF2	MF2	MF3
MF2	MF1	MF2	MF2	MF3	MF4
MF3	MF2	MF2	MF3	MF4	MF4
MF4	MF2	MF3	MF4	MF4	MF5
MF5	MF3	MF4	MF4	MF5	MF5

4. RESULT AND DISCUSSION

The multi-area EV incorporated model is examined by applying an unpredicted load fluctuation in control area 1. The constraints of the employed PID, FPID, and FFPID controllers are adjusted by ARO technique with the application of 0.01 p.u. sharp load variation in control area 1. The ITAE also known as integral time absolute error in (2) is act as fitness function for the said tuning process. The suitable tuned controller constraints obtained with ARO process is tabulated under Table 3. The capability of the controllers is judged by observing the oscillations of frequency in control area and interline power, portrayed by Figures 4 and 5 respectively. The mathematical computation of maximum positive deviation (overshoot), settling time and minimum negative deviation (undershoot) of system responses are carried out and tabulated in Table 4. The said Table shows the dominance of FFPID controller over FPID and PID controller as the former controller possess the better values of the response specifications. Further the flexibility of the implemented FFPID controller is established by following robustness analysis.

$$ITAE = \int_0^t (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|).\, tdt \qquad (2)$$

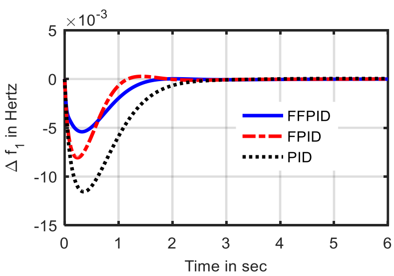

Figure 4. Oscillations of frequency of area 1 due to demand variation in control area 1

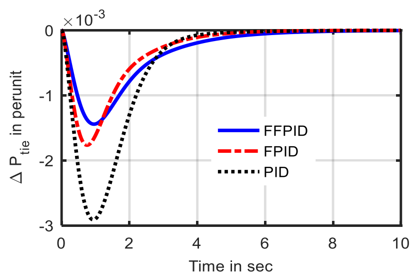

Figure 5. Oscillations of interline power due to demand variation in control area 1

Table 3. ARO tuned optimum controller gains

Controller	Control area 1						Control area 2					
	C_{p1}	C_{p2}	C_d	C_i	λ	μ	C_{p1}	C_{p2}	C_d	C_i	λ	μ
FFPID	1.463	0.9811	1.7541	1.0221	0.81	0.97	1.7910	0.4811	1.2203	1.9501	0.99	0.79
FPID	1.842	1.0122	1.7456	1.9741	NA	NA	1.5542	0.1423	1.0789	1.5247	NA	NA
PID		C_p		C_i		C_d		C_p		C_i		C_d
		1.3154		1.9864		0.2147		1.1258		0.5963		1.2456

Table 4. Response evaluative specifications of the scrutinized model with FFPID, FPID, and PID controllers

Controller	Δf_1			Δf_2			ΔP_{tie}		
	U_{sh} in Hz	T_s in sec	$O_{sh} \times 10^{-3}$ Hz	U_{sh} in Hz	T_s in sec	$O_{sh} \times 10^{-3}$Hz	U_{sh} in p.u.	T_s in sec	$O_{sh} \times 10^{-3}$ p.u.
PID	-0.0116	2.0893	0.04649	-0.0066	3.3720	0.02388	-0.0029	2.6434	0
FPID	-0.0081	1.0886	0.2709	-0.0027	2.1713	0.0004	-0.0018	2.6339	0
FFPID	-0.0054	1.0288	0.0227	-0.0022	2.0786	0	-0.0014	2.5630	0

4.1. Robustness analysis with random demand variations

The implemented FFPID controller in the multi-area system is considered to be robust if it can settle the abnormalities of any kind of unpredicted load fluctuations. To analyze this, the EV integrated model is subjected to random demand variations in control area 1 and the system responses are examined in terms of interline power oscillations and frequency deviations in both control areas. The shape of the random demand variations and system responses are displayed in Figure 6. This Figure evidence the robustness capability of the considered FFPID controller as it damps out the oscillations of frequency and interline power and make the system stable in a better manner.

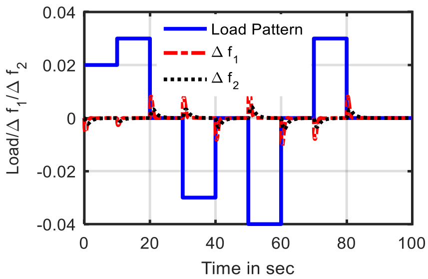

Figure 6. Oscillation of interline power and area frequency due to random demand deviation

4.2. Robustness analysis with system parameters variations

As an extension of robustness check the constraints or the nominal parameters of the system are subjected to a wide range of deviations and the responses of the system are examined. Some constraints like regulation index (R) and bias index (B) of the examined model as shown in Figure 1 are varied $\pm 50\%$ and $\pm 25\%$ and the performance evaluative indices i.e., maximum positive deviation(overshoot), settling time and minimum negative deviation(undershoot) are obtained and tabulated in Table 5. From these evaluative indices it can be seen that the maximum positive deviation (overshoot), settling time and minimum negative deviation (undershoot) are not changing widely even the constraints R and B are changing widely. The analysis again witnesses the robustness behavior of the projected FFPID controller.

Table 5. Response evaluative specifications due to variation of system constraints

System constraints	% age variation	U_{sh} for Δf_1 (in p.u.)	T_s for Δf_1 (in sec)	$O_{sh} \times 10^{-3}$ for Δf_1 (in p.u.)	U_{sh} for ΔP_{tie} (in p.u.)	T_s for ΔP_{tie} (in sec)	$O_{sh} \times 10^{-3}$ for ΔP_{tie} (in p.u.)
R	-50%	-0.0052	1.0311	0.0234	-0.0017	2.5669	0
	-25%	-0.0053	1.0299	0.0231	-0.0016	2.5644	0
	+25%	-0.0052	1.0300	0.0233	-0.0015	2.5654	0
	+50%	-0.0051	1.0321	0.0235	-0.0016	2.5678	0
B	-50%	-0.0051	1.0312	0.0235	-0.0017	2.5673	0
	-25%	-0.0052	1.0298	0.0233	-0.0014	2.5654	0
	+25%	-0.0054	1.0311	0.0234	-0.0013	2.5666	0
	+50%	-0.0051	1.0322	0.0236	-0.0016	2.5681	0

5. CONCLUSION

The research analysis confirmed the dominance of fractional fuzzy-PID (FFPID) controller over FPID and PID controller in the multi generation unified power system. The Multi-area model considered the nonlinear EV aggregators, SMES along with thermal power sources for evidencing the frequency deviation control. The result analysis and robustness analysis showed that the implemented controller successfully regulates the deviations of area frequency and interline power during unpredicted load disturbance in control areas. The random loading application and parameter alteration further proved the ability of the projected FFPID controller. Response specifications like maximum positive deviation (overshoot), settling time, and minimum negative deviation (undershoot) are calculated for evidencing the dominance of the said FFPID controller over FPID and PID controller.

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