

## AUTOMATIC GENERATION CONTROL USING A FRACTIONAL ORDER CASCADE CONTROLLER

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### ABSTRACT

*The frequency stability of power systems depends on the active power balance between the generation and demand. The varying nature of the demand upsets this balance which consequently results in the deviation of the frequency of the system from its nominal value. In order to stabilize the frequency, the generation is continuously adjusted with the help of a controller to match the load at all times. This control process is called automatic generation control. This study proposes a new structure of fractional order cascade controller, namely fractional order proportional integral – fractional order tilt integral derivative (FOPI-FOTID) controller for automatic generation control (AGC) of a four-area deregulated power system. The parameters of the controller were optimized using the Grasshopper Optimization Algorithm (GOA). The superiority of the proposed controller was evaluated by comparing its performance against a non-cascade FOTID controller and a cascade tilt integral – tilt integral derivative (TI-TID) controller, under a step load perturbation in the power system. The recorded improvements over the cascade TI-TID controller are: 47%, 18.7%, 30.7% and 23.04% for the settling time, and 56.9%, 70.9%, 62.6% and 56.86% for the undershoot of the frequency deviations of area-1, area-2, area-3 and area-4 respectively; 32.86%, 3.13% and 23.0% for the overshoot of the frequency deviations of area-2, area-3 and area-4 respectively.*

**Keywords:** Automatic generation control; Fractional order calculus; Cascade control; Power system

### 1. INTRODUCTION

The reliable, efficient operation of the power system depends on the active power balance between generation and load demand. Any form of disturbance that will upset the active power balance such as change in load demand or failure of some generating units, leads to deviation in frequency and tie-line power flow schedules (Abdelaziz and Ehab, 2016). Large frequency deviation degrades the performance of frequency-dependent loads in the power system, damages electrical equipment, and affects the performance of protection schemes (Dash, Saikia, and Sinha, 2016). The aim of automatic generation control (AGC) is to minimize the frequency deviation and regulate tie-line power flows by continuously adjusting the generation in order to maintain the active power balance (Debnath *et al.*, 2016).

The AGC controls the frequency via two layers of control; primary and secondary.

The primary frequency control utilizes the speed governing mechanism to regulate the generation. However, it produces a steady state error in the frequency especially if the imbalance is too large. The secondary/supplementary controller, which is basically an integral action, eliminates the steady state error and returns the frequency to its nominal value.

Several control approaches have been suggested for the supplementary control AGC such as classical control approach, adaptive control, neural network, optimal control, robust control, variable structure control, and fuzzy logic control as reported in different review papers (Hote and Shivam, 2018). Most of these control strategies are difficult

to implement due to their structural complexity. The popularity, simplicity, ease of use and clear functionality of classical PID control technique encouraged more studies on their application for AGC (Debnath et al., 2016). The article by Hote and Shivam (2018) presented a brief review for the application of PID controller as supplementary controller for AGC, together with its present and future challenges.

Recently, growing interest in improving the performance of conventional PID controllers has led to significant attention toward fractional order controllers, which are based on fractional calculus. Unlike traditional calculus, fractional calculus accommodates non-integer order of differentiation and integration (Prakash *et al.*, 2019). In other words, it can be regarded as a generalization of integration and differentiation to non-integer order. Even though fractional calculus is almost as old as traditional calculus, it was few decades ago that its application in the area of control theory emerged i.e., through the advent of fractional order controllers (Jena *et al.*, 2020). There are four classes of fractional order controllers found in literature; fractional order PID (FOPID), tilt integral derivative (TID), CRONE and fractional lead-lag compensators. The FOPID and TID controllers were formed by modifying the conventional PID controller. In addition to the proportional, integral and derivative gains of PID, FOPID controller has two more parameters; integration and differentiation order. This makes the parameters of FOPID to be five as against three for PID, thereby giving it more degree of freedom and more flexibility in design. The TID controller presented as a patent in (USA Patent No. 5371670, 1994) is obtained by replacing the proportional block of the PID with a tilted component, which results in an optimum response that is closer to the hypothetical optimal response found by Bode. It has been reported by Chen and Petr (2009) that fractional order controllers offer more flexibility in adjusting gain and phase characteristics than conventional integer order controllers. Consequently, they outperform the non-integer controllers in achieving a robust control system design (Taher, Fini, and Aliabadi, 2014).

Moreover, different combinations of fractional order controllers in cascade configuration have been applied in

power systems to effectively solve the AGC problem. Cascade configuration of controllers is a concept that utilizes two controllers operating in two control loops i.e. the inner and outer loop. The outer loop is referred to as the master or primary loop while the inner loop is referred to as the secondary or slave loop (Dash, Saikia, and Sinha, 2016). Its advantages over normal classical controllers are fast disturbance rejection and better dynamic response. A three degree-of-freedom PID (3-DOF-PID) and TID controllers were adopted in cascade configuration for AGC, as master and slave controllers respectively (Guha, Roy, and Banerjee, 2021). Prakash et al., (2019) proposed a cascade structure of two – degree of freedom proportional integral controller and fractional order proportional integral derivative controller with filter (2DOF-PI-FOPIDN) for AGC of multi-source interconnected power system including HVDC tie-link in a restructured environment. A two-degree of freedom Fractional order PID with derivative filter cascaded with Proportional derivative filter (2DOF-FOPIDN-PDN) was applied for AGC of a two-area power system consisting of renewable and conventional sources by (Jena *et al.*, 2020). A cascade tilt integral – tilt integral derivative (TI-TID) controller structure was proposed by Kumari and Shankar (2020) for a four-area deregulated power system. A proportional derivative controller in cascade with fractional order PID (PD-FOPID) was employed by Nayak *et al.* (2020) for AGC of two-area interconnected power system.

It could be observed from the aforementioned studies that the controller structures were formed majorly from FOPID and TID controllers and their variants. Recently, a new fractional order controller structure formed by hybridizing FOPID and TID to form Fractional Order Tilt Integral Derivative (FOTID) controller has been introduced by Priyadarshani et al (2020) and was shown to be more effective than both TID and FOPID. A cascade fractional order structure utilizing the new hybrid fractional order controller has so far not been utilized for AGC studies. This study proposes a fractional order PI – fractional order tilt integral derivative (FOPI-FOTID) controller as a new fractional order cascade controller structure for AGC.

In order to obtain an optimal response for a given controller, optimization algorithms are used to obtain its optimal parameters. According to the 'No Free Lunch Theorem', if algorithm A outperforms algorithm B in a given application, algorithm B might outperform algorithm A in another application. Hence, researchers have been trying different optimization algorithms in several AGC studies. The optimization algorithms are inspired by natural processes such as genetic variation and natural selection for Genetic Algorithm, foraging behaviour of ants for Ant Colony Optimization, social behaviour of animals for Particle Swarm Optimization. In this study, Grasshopper Optimization Algorithm (GOA), which derives its inspiration from the swarming behaviour, will be utilized in obtaining the opti-

num parameters of the proposed controller.

The objectives of this study include:

- i. Development of the proposed FOPI-FOTID controller as supplementary controller for AGC of a four-area deregulated power system.
- ii. Optimization of the parameters of the proposed controller using the Grasshopper Optimization Algorithm (GOA).
- iii. Replication of FOTID controller for comparison with the proposed FOPI-FOTID controller.
- iv. Comparison of the performance of the proposed controller with cascade TI-TID controller presented by (Kumar and Shankar, 2020).

## 2. POWER SYSTEM MODEL

The study was conducted on a four-area deregulated thermal power system model consisting of two GENCOs in each area, two DISCOs each in area-1 and area-3, and one

DISCO each

in area-2 and area-4. The simplified diagram of the model is shown in Figure 1.

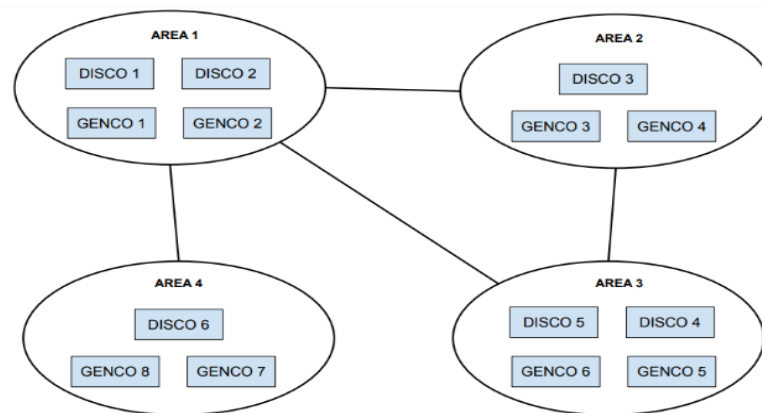


Figure 1: Simplified diagram of the power system model

The major components of a given area in a power system are; governor, turbine, alternator and load ((Hote and Shivam, 2018)). These components have complex non-linear dynamics. However, for the purpose of AGC studies, their transfer function models can be approximated by a linear model represented by a first order transfer function. The transfer function model of the different power system components is given as follows:

Governor:

$$G_g(s) = \frac{1}{T_g s + 1} \quad (1)$$

Turbine:

$$G_t(s) = \frac{1}{T_t s + 1} \quad (2)$$

Load and machine:

$$G_{lm}(s) = \frac{1}{2Hs + D} \quad (3)$$

The incremental tie-line between two interconnecting areas is given as:

$$\Delta P_{tie,ij} = \frac{2\pi T_{ij}}{s} (\Delta F_i(s) - \Delta F_j(s)) \quad (4)$$

The generalized model of the *i*-th area of a deregulated power system model consisting of two identical thermal units in each area is given in Figure 2.

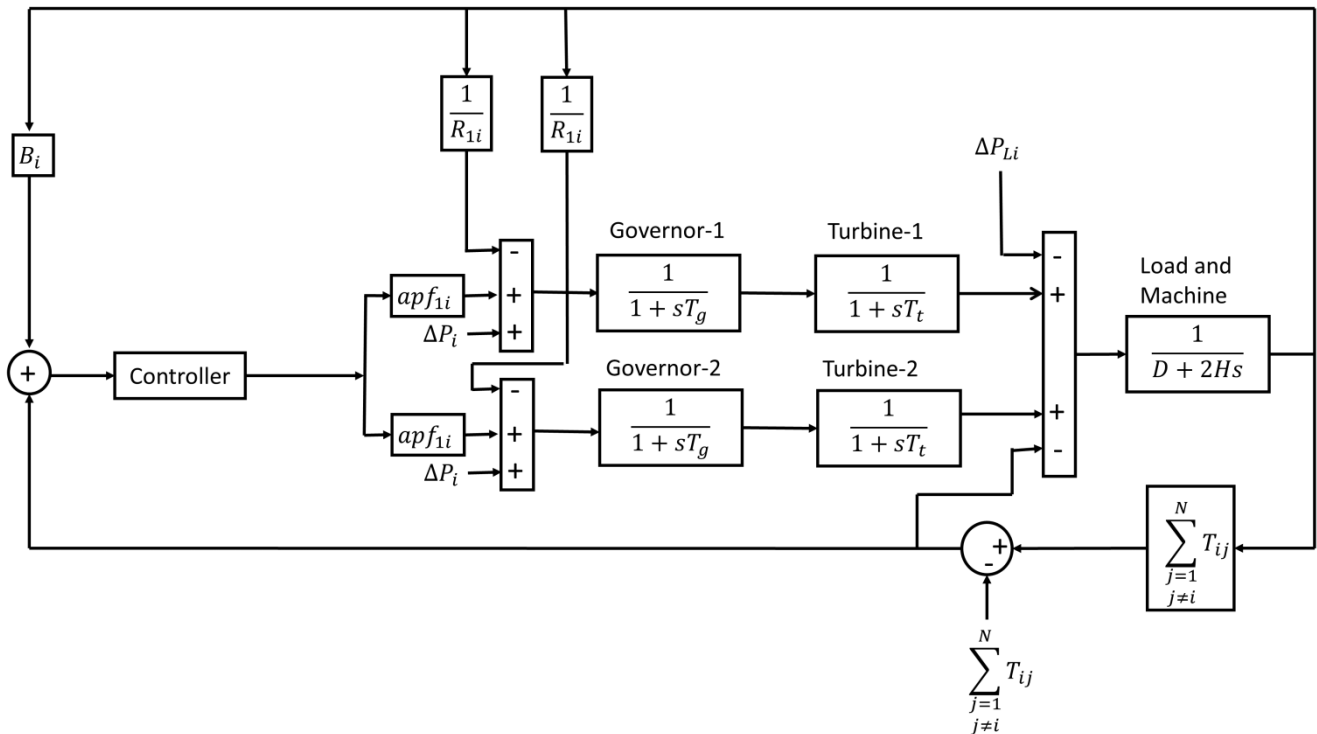


Figure 2: Generalized model of *i*-th area power system (Kumari and Shankar, 2020)

In a deregulated power system, each DISCO is at liberty to contract power from any GENCO. Therefore, there could be many possible arrangements of GENCO-DISCO contracts. In order to visualize the contracts, the concept of DISCO Participation Matrix (DPM) was proposed by Donde *et al.*, (2001). DPM is a  $n \times m$  matrix where  $n$  represents the number of GENCOs and  $m$  represents the number of DISCOS. Each entry of a DPM is known as contract participation factor (*cpf*). A *cpf* can be defined as a fraction of the total load contracted by a DISCO (column) to a GENCO (row). The general structure of DPM with  $n$  GENCOs and  $m$  DISCOs can be expressed in Equation (5);

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & \dots & \dots_{(m-1)} & cpf_{1m} \\ cpf_{21} & cpf_{22} & \dots & \dots_{(m-1)} & cpf_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ cpf_{(n-1)1} & cpf_{(n-1)2} & \dots & \dots_{(m-1)} & cpf_{(n-1)m} \\ cpf_{n1} & cpf_{n2} & \dots & \dots_{(m-1)} & cpf_{nm} \end{bmatrix} \quad (5)$$

In a given area, there may be several GENCOs. Area Control Error (ACE) signal has to be distributed among them according to their participation in AGC. The ACE participation factors (*apf*) are coefficients that distribute the ACEs to the GENCOs in a given area. The total sum of the factors for a given GENCO must be equal to 1 as shown in Equation (6)

$$\sum_i^{NGENCO_j} apf_{ji} = 1 \tag{6}$$

The demands of a particular DISCO must be met by GENCOs contracted to it. Therefore, as particular sets of GENCOs are supposed to follow the load demanded by a DISCO, information signals must flow from a DISCO to a particular GENCO specifying corresponding demand. The demands are specified by *cpf*s and the *pu MW* of a DISCO. The contracted power supplied by the *i*-th GENCO is given in Equation (7);

$$\Delta P_i = \sum_{j=1}^m cpf_{ij} \Delta P_{Lj} \tag{7}$$

For a given two interconnected areas labelled area-1 and area-2, having two GENCOs and two DISCOs each, the scheduled steady-state power flow on the tie-line is given in

Equation (8);

$$\Delta P_{tie,12}^{scheduled} = \sum_{i=1}^2 \sum_{j=3}^4 cpf_{ij} \Delta P_{Lj} - \sum_{i=3}^4 \sum_{j=1}^2 cpf_{ij} \Delta P_{Lj} \tag{8}$$

At any given time, the tie-line error is expressed in Equation (9):

$$\Delta P_{tie,12}^{error} = \Delta P_{tie,12}^{actual} - \Delta P_{tie,12}^{scheduled} \tag{9}$$

The error in tie-line power deviation  $\Delta P_{tie,12}^{error}$  vanishes in the steady-state as the actual tie-line power flow reaches the scheduled power flow. This error signal is used to generate the respective ACE signals as in the traditional case;

$$ACE_1 = B_1 \Delta f_1 + \Delta P_{tie,12}^{error} \tag{10}$$

$$ACE_2 = B_2 \Delta f_2 + a_{12} \Delta P_{tie,12}^{error} \tag{11}$$

### 3. STRUCTURE OF PROPOSED CONTROLLER

The proposed controller is a cascade combination of Fractional Order proportional Integral (FOPI) and Fractional

Order Tilt Integral Derivative (FOTID) controllers as shown in Figure 3.

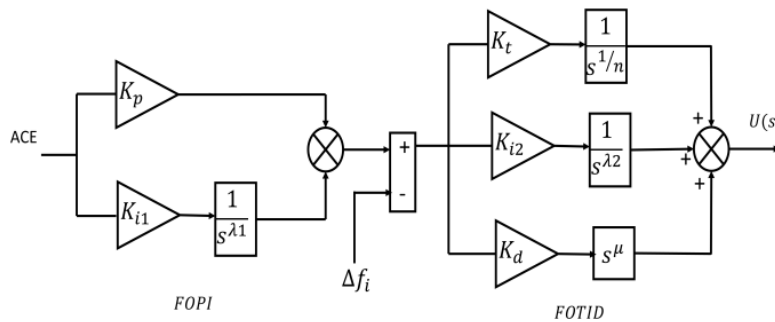


Figure 3: Structure of proposed controller

The FOPI controller consists of proportional gain  $K_p$ , integral gain  $K_{i1}$ , and fractional integration order  $\lambda_1$ . The FOTID is a hybridized controller formed by combining the components of FOPID and TID controllers. It consists of the tilt gain  $K_t$ , integral gain  $K_{i2}$ , fractional integration

order  $\lambda_2$ , derivative gain  $K_d$ , and fractional differentiation order  $\mu$ . The transfer functions of the primary and secondary controllers are given in Equations (12) and (13) respectively;

$$C(s)_{FOPI} = K_p + \frac{K_{i1}}{s^{\lambda_1}} \quad (12)$$

$$C(s)_{FOTID} = \frac{K_t}{s^{1/n}} + \frac{K_{i2}}{s^{\lambda_2}} + K_d s^\mu \quad (13)$$

#### 4. FORMULATION OF OPTIMIZATION PROBLEM

The problem was formulated as an optimization problem with the objective of minimizing the Integral Time Absolute Error (ITAE) of the deviations in frequency and tie-line power flow schedules between interconnected areas. The minimum and maximum values of the controller parameters taken as set of constraints.

Minimize,

$$J = ITAE = \sum_{i=1}^N \int_0^t \left( |\Delta f_i(t)| + \sum_{\substack{j=1 \\ j \neq i}}^N |\Delta P_{tie(i-j)}(t)| \right) \times t \times dt \quad (14)$$

Subject to;

$$\alpha^{\min} \leq \alpha \leq \alpha^{\max} \quad (15)$$

where  $\alpha$  is parameter values of the controller. The minimum and maximum values of the controller gains and the differentiation and integral order were taken to be 0 and 2 respectively. The optimization problem was solved using the grasshopper optimization algorithm (GOA).

#### 5. GRASSHOPPER OPTIMIZATION ALGORITHM

The GOA is a metaheuristic optimization algorithm that was first presented by Saremi, et al (2017), and it derives its inspiration from the swarming behavior of grasshoppers. Grasshoppers are insects that are considered as pests due to the harm and destruction they cause to crops. Grasshoppers can be found mostly individually, yet they form one of the largest swarm of all creatures. The life cycle of grasshopper starts from egg to nymph to adult. One interesting feature about grasshopper is that they form swarms both in the nymph and adult stage, whose characteristics are used to model the exploitation and exploration of search spaces required by metaheuristic algorithms. The swarm formed by

grasshoppers in the nymph stage is characterized by slow movement and small steps, which is used in mimicking the exploitation of the search space. The exploration of the search space is mimicked by the swarm behavior in adult stage whose feature is long range and abrupt movement. Another important characteristic of the grasshopper swarm is food source targeting. The exploration, exploitation and food source targeting characteristics of the grasshopper swarm are mathematically modeled to obtain the GOA and are described in details in the paper titled, *Grasshopper Optimization Algorithm: Theory and Application* by Saremi, et al (2017).

#### 6. RESULTS AND DISCUSSIONS

The study of the performance of the proposed controller for the four-area deregulated power system model was carried out through computer simulations. The model was developed in Matlab/Simulink R2013a environment. The code for the GOA was executed as an m-file. The power system model was simulated by running the GOA, based on the Also available online at <https://www.bayerojet.com>

parameters presented in Table 1, with the objective of minimizing the ITAE to determine the optimum parameters of the proposed FOPI-FOTID controller and FOTID controller.

The study was carried out under bilateral transaction scenario as given by the DPM in Equation (16) and upon a step

load demand of DISCOs as follows;  $\Delta P_{L1} = 0.1 pu$  ,  
 $\Delta P_{L2} = 0.05 pu$  ,  $\Delta P_{L3} = 0.1 pu$  ,  $\Delta P_{L4} = 0.08 pu$  ,  
 $\Delta P_{L5} = 0.06 pu$  and  $\Delta P_{L6} = 0.1 pu$

Table 1: GOA parameters

Parameter	Value
Number of search agents	100
Number of iterations	200
Maximum coefficient, $c_{max}$	1
Minimum coefficient, $c_{min}$	0.00001

$$DPM = \begin{bmatrix} 0.4 & 0 & 0 & 0 & 0.8 & 0 \\ 0 & 0.2 & 0 & 0.4 & 0 & 0 \\ 0.4 & 0 & 0.4 & 0 & 0 & 0 \\ 0 & 0.4 & 0 & 0.2 & 0 & 0 \\ 0.2 & 0 & 0 & 0.4 & 0 & 0 \\ 0 & 0 & 0.6 & 0 & 0.2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0.4 & 0 & 0 & 0 & 0.5 \end{bmatrix} \quad (16)$$

The dynamic response of the proposed controller and FOTID controller were observed and compared. The graphical responses of the frequency deviations are given in Figure 4.

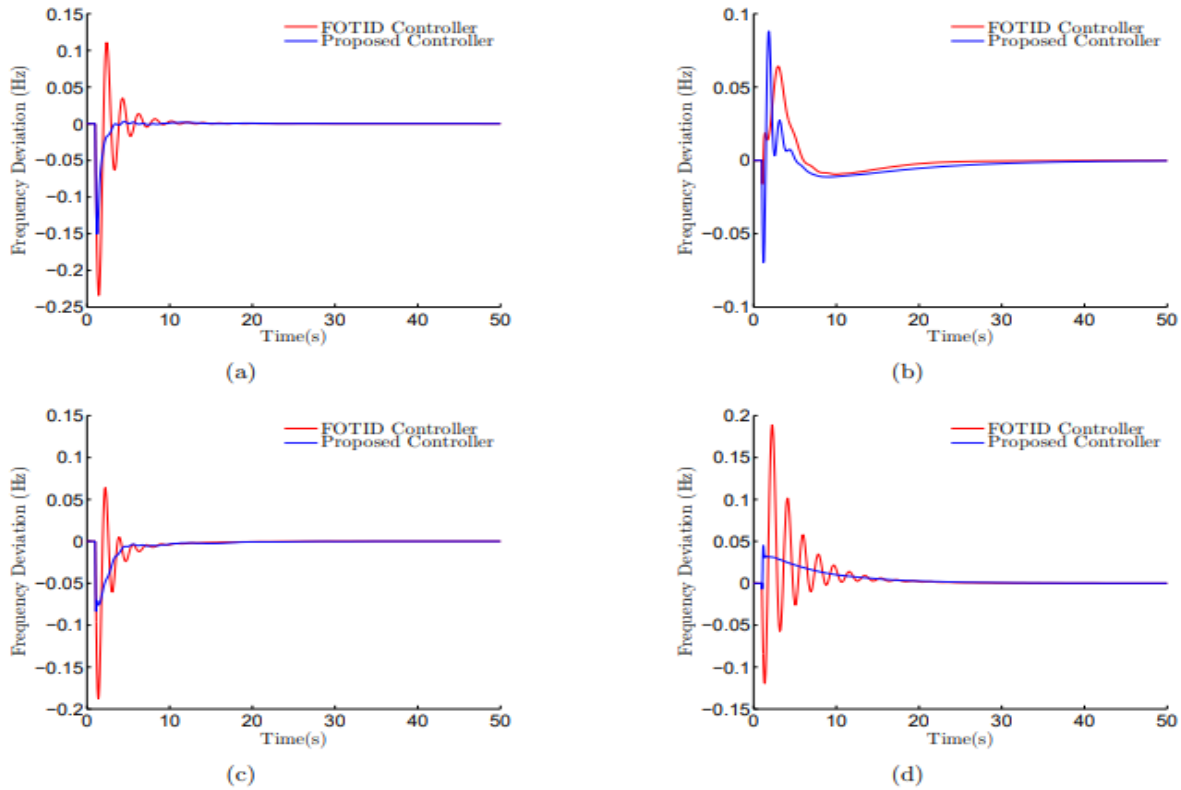


Figure 4: Transient response of the frequency deviations in areas 1,2,3 and 4 respectively

It could be observed from Table 2, the proposed controller offers improvements in the settling time of  $\Delta f_2$ ,  $\Delta f_3$  and  $\Delta f_4$  by 7.74%, 16.21% and 4.03% respectively over the FOTID controller. Significant improvements were recorded

for the overshoot and undershoot of the frequency deviations. A decrease of 97.6%, 67.7%, 55.6% and 75.3% for the overshoot of  $\Delta f_1$ ,  $\Delta f_2$ ,  $\Delta f_3$  and  $\Delta f_4$  were recorded by the proposed controller over the FOTID controller.

Table 2: Comparison of performances of the controllers

Settling Time (secs)				
Controller	$\Delta f_1$	$\Delta f_2$	$\Delta f_3$	$\Delta f_4$
Proposed Controller	3.1862	14.1876	10.1099	17.5728
FOTID controller	8.5398	15.6366	17.3553	27.1175
CC-TI-TID (Kumar 2020)	19.3520	21.1130	19.1030	29.9720
Overshoot (p.u)				
Proposed Controller	0.0030	0.1317	0.0010	0.0451
FOTID controller	0.1108	0.0787	0.0639	0.1818
CC-TI-TID (Kumar 2020)	0.0680	0.1340	0.0670	0.1010
Undershoot (p.u)				
Proposed Controller	0.1503	0.0526	0.0833	0.004
FOTID controller	0.2341	0.0952	0.1877	0.1818
CC-TI-TID (Kumar 2020)	0.4740	0.4130	0.4980	0.265

The proposed controller offers a significant improvement over the published CC-TI-TID controller by Kumar and Shankar (2020) as it produced lesser settling time and lower undershoot and overshoot of the frequency deviation in all areas. As shown in Table 2, an improvement of 47%, 18.7%, 30.7% and 23.04% was achieved in the settling time of the frequency deviation in area-1, area-2, area-3 and ar-

ea-4 respectively. Similarly, for the undershoot, the proposed controller produced a 56.9% improvement in  $\Delta f_1$ , 70.9% in  $\Delta f_2$ , 62.6% in  $\Delta f_3$  and 56.89% in  $\Delta f_4$ . Even though the proposed controller offers deterioration in the overshoot of  $\Delta f_1$  by 76.9%, it still offers improvement in the overshoot of  $\Delta f_2$ ,  $\Delta f_3$  and  $\Delta f_4$  by 32.98%, 3.13% and 23.0% respectively.

## 7. CONCLUSION

In this study, a structure of fractional order cascade controller, namely FOPI-FOTID controller was proposed for the AGC of a four-area deregulated power system model. The optimal parameters of the proposed controller were obtained using the GOA. Simulation studies were conducted to analyze its performance and it was found that it gives better dynamic response than a non-cascade FOTID controller in terms of settling time, albeit with little improvement in terms of overshoot and undershoot. Significant improvements were recorded by the proposed controller in all the performance indices by comparison against a different

structure of fractional order cascade controller, namely TI-TID controller published in another work. The recorded improvements are; 47%, 18.7%, 30.7% and 23.04% for the settling time of  $\Delta f_1$ ,  $\Delta f_2$ ,  $\Delta f_3$  and  $\Delta f_4$  respectively; 56.9%, 70.9%, 62.6% and 56.86% for the undershoot of  $\Delta f_1$ ,  $\Delta f_2$ ,  $\Delta f_3$  and  $\Delta f_4$  respectively; 32.86%, 3.13% and 23.0% for the overshoot of  $\Delta f_2$ ,  $\Delta f_3$  and  $\Delta f_4$  respectively; Based on the results obtained, it can be concluded that the proposed controller offers superior dynamic performance compared to the non-cascade FOTID and cascade TI-TID controllers.

## APPENDIX

Values of system parameters;  $R_i = 0.05 \text{ Hz/pu MW}$  ,  $0.425 \text{ pu MW/Hz}$  ,  $T_{ij} = 0.245$  ,  $H_i = 5.0$  ,  $D_i = T_{gi} = 0.08s$  ,  $T_{ti} = 0.3s$  ,  $P_{ri} = 1000 \text{ MW}$  ,  $B_i = 0.8 \text{ pu MW/Hz}$

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