Design of Quasi-Oppositional-Based CSA Optimized Cascade Pi-Fractional Order PID Controller for Interconnected Power System

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Abstract In this work, an adequate approach is depicted to endorse the superiority of cascade PI-fractional order PID (PI-FOPID) controller over PID and FOPID controllers and also to validate the quasi-oppositional-based crow search algorithm (QOCSA) to elect the peerless gains of the controllers over CSA algorithm. PI-FOPID controller is implemented in an interconnected reheat-thermal power system to amend system performances. The system is designed with nonlinearity such as generation rate constraint (GRC) and ITAE as fitness function. The fundamental intention of this system is to diminish the divergence of frequency and power. For this purpose, a hybrid QOCSA and CSA algorithms are implemented to determine the significant parameters of controllers by which the divergence reducing competence of controller can be improved. This analysis to substantiate the proposed PI-FOPID controller and QOCSA algorithm is accomplished with a step load of 0.01 p.u. injected in area-1. Finally, QOCSA is substantiated over CSA algorithm, and PI-FOPID controller is confirmed as an excel controller over FOPID and PID controllers.

Keywords Automatic generation control (LFC) · PID · Fractional order PID (FOPID) controller · Cascade controller · Crow search algorithm (CSA)

1 Introduction

In recent power system, divergence of frequency and power exceedingly influences the stability and security of the entire interconnected system. The primary causes of the frequency instability are precipitous load fluctuation, fault, etc. The load

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fluctuation is very frequent and cannot be regulated. The interconnected system is eminently influenced by this fluctuation of load, and the divergence of frequency raised by this fluctuation may be circulated throughout the interconnected system. Primary control scheme (droop) is a fast response control scheme, but it is incapable to restore the system frequency. Secondary control schemes such as automatic generation control (AGC) are highly effective to maintain the steady-state frequency response of the system. AGC is an admirable control scheme to contribute reliable, stable, and economic power to consumer [1, 2]. The central objective of AGC is to counterbalance the load demand and generation by coordinating the valve position of generators.

Different structures of PID controllers such as PID, PI-PD, PD-PID, 2DOF PID, IDD, FOPID, 3DOF PID, and 3DOF FOPID controllers have enforced to achieve the surpass performance of frequency divergence [3–12]. Some researchers have blended FLC with PID controller to accomplish better performance of nonlinear power system [13–19].

Computational/optimization techniques are absolutely significant tools to achieve admirable improvement of frequency response by plucking pertinent pairs of controller gains. The pertinent parameters of controllers are highly responsible for the responses of the power system. Different optimization algorithms with capability to figure out the optimal point of the search space are eminently obligatory. In AGC, some optimization algorithms such as DE, BBO, and CSA algorithms are enforced prosperously to achieve optimal controllers [6, 11, 16]. Single optimization algorithm may not competent enough to boost the performance admirably. For this purpose, some researchers have designed hybrid or adaptive optimization algorithms which are realized in this field. DEPSO [20], LUS-TLBO [17], ASOS [21], and MGHS [22] are some modified/hybrid algorithms enforced fruitfully in this field.

In this work, cascade PI-FOPID controller is proposed by blending PI and FOPID controllers. This proposed controller is enforced in interconnected power system which is substantiated over FOPID and PID controllers. The optimal PI-FOPID controller is achieved by using crow search algorithm (CSA) proposed by Askarzadeh [23]. CSA algorithm is modified by some researchers with better competence to solve complex problems such as PGCSA and DECSA [24, 25]. Quasi-oppositional-based CSA (QOCSA) is proposed to boost the power system responses over CSA.

2 Power System Modeling

The interconnected power system considered for this analysis is a reheat-thermal power system. This power system is proposed with generation rate constraint (GRC) as shown in Fig. 1. Each area of the power system has capability to generate 2000 MW. The nonlinearity (GRC) is considered to design a more realistic power system. The responses of power system are eminently manipulated by GRC. Generally, GRC with 3%/min ($\pm$ 0.0005) is preferred for thermal power plant. Appendix 1 consists the gain and time constants of power system. An immediate load variation of 1% in area-1

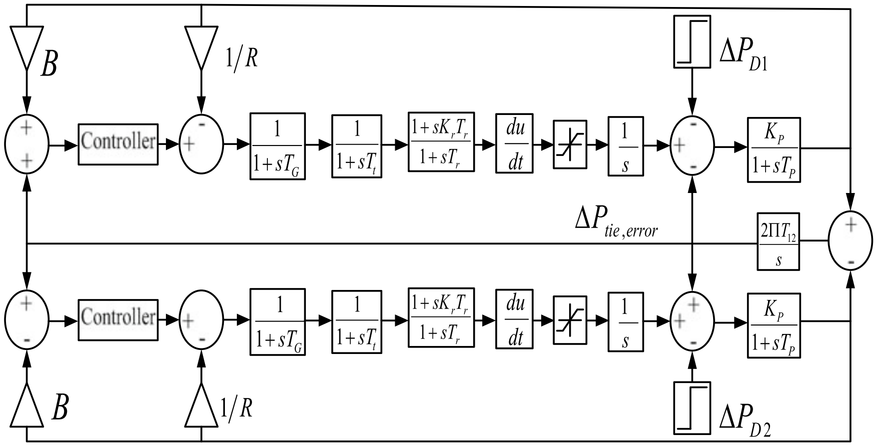

Fig. 1 Power system model

is applied to realize the system responses with proposed controller and optimization algorithm. The errors appear in areas (area control error-ACE) are characterized in Eqs. 1 and 2.

$$\text{ACE}_1 = B_1 \Delta f_1 + \Delta P_{\text{tie,error}} \tag{1}$$

$$\text{ACE}_2 = B_2 \Delta f_2 + \Delta P_{\text{tie,error}} \tag{2}$$

where, B_1 and B_2 are frequency bias factors.

Integral time absolute error (ITAE) is adopted as fitness function of the system to minimize the divergence of both frequency and tie-line power. The expression of the fitness function is described in Eq. (3).

$$\text{ITAE} = \int_0^T t(\Delta f_1 + \Delta f_2 + \Delta P_{\text{tie,error}}) \tag{3}$$

3 Purposed Cascade PI-FOPID Controller

The purposed PI-FOPID controller has two closed loops such as inner and outer loops. These two loops are constructed in such a way that the output of each loop behaves as input of other loop. The structure of proposed controller is illustrated in Fig. 2 [5]. As FOPID controller is flexible and competence enough to handle supply

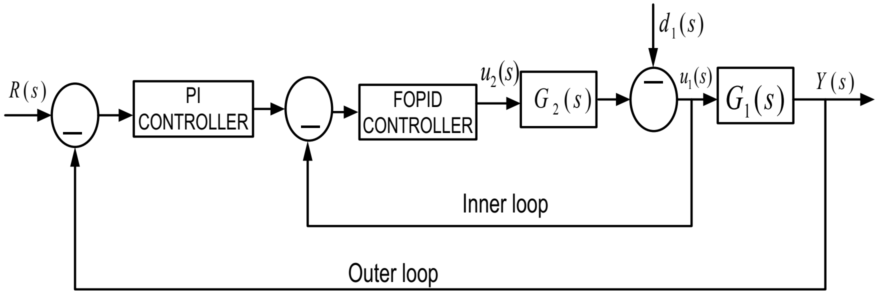

Fig. 2 Cascade controller structure

disorder by which the reliability of outer loop is enhanced. The PI controller is used as outer loop measure to administer the output quality of the system. The noise reduce capability of the controller is the advantage.

3.1 Outer Loop

The mathematical expression of the outer loop process is characterized as below. This loop is characterized by concerning process output $Y(s)$, process of outer $G_1(s)$ and load distortion $d_1(s)$ as

$$Y(s) = G_1(s)U_1(s) + d_1(s)$$

$Y(s)$	Output of the process.
$G_1(s)$	Outer process.
$d_1(s)$	Load disturbance.
$U_1(s)$	Input of the process.

The referral error is eliminated by the outer loop.

3.2 Inner Loop

The expression of inner loop is expressed as

$$y_2(s) = G_2(s)U_2(s)$$

The inner loop output is delivered as input to the outer loop, i.e., $y_2(s) = U_1(s)$. The error in the inner loop is regulated by inner loop. The rapidity of inner measure (FOPID controller) highly affects the response of the controller. The expression of the proposed controller is

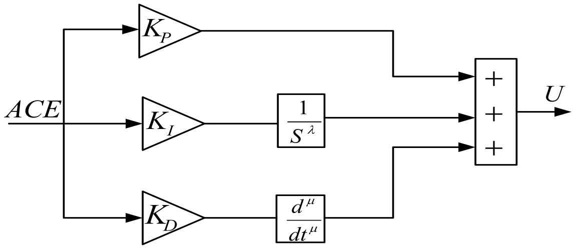

Fig. 3 Fractional order PID controller structure

$$Y(s) = \left[\frac{G_1(s)G_2(s)C_1(s)C_2(s)}{1 + G_2(s)C_2(s) + G_1(s)G_2(s)C_1(s)C_2(s)}\right]R(s) + \left[\frac{G_1(s)}{1 + G_2(s)C_2(s) + G_1(s)G_2(s)C_1(s)C_2(s)}\right]d_1(s)$$

In this work, PI and FOPID controllers are considered as outer loop and inner loop respectively and the structure of fractional order PID controller is illustrated in Fig. 3.

4 Quasi-Oppositional-Based Crow Search Algorithm (QOCSA)

Crows are opted as the preeminent smart bird. Compared to their environmental structure, they have enormous brain. Crows cover up their overabundance food in undoubted location and the crow redeems the food when necessary. Crows attain foods by doing a great team work always. Hiding foods for future is not simple for them because some challenger crows can also come after to follow the food. At that moment, the crow endeavors to cheat by altering the direction in the colony. The position in the colony is acknowledged as food position. Crows divert the hiding nourishment of other crows by tracking them, and at the same time, the crows take some auxiliary avoidance like altering the concealing places to stay away from becoming an upcoming easy target. By conceding these, clever action CSA algorithm has established [23].

The oppositional-based learning (OBL) was introduced by Tizhoosh [26]. The prime object of this approach is to increase the skill of the result and to stimulate the diversity factor toward the optimal solution by concerning the opposite point of the particle.

The steps followed for QOCSA algorithm are described as

1. Initialize the flock of crows of size $X_{[\mathrm{NP} \times D]}$ within the restraint 0.001–2.
2. Initialize the memory of crows of size $M_{[\mathrm{NP} \times D]}$.
3. Determine the opposite position of the initial matrix as below

$$\mathrm{MO}_j = \frac{\mathrm{para}^{\min} + \mathrm{para}^{\max}}{2}$$

M_j is the middle of the search space. The opposite position of initial matrix (X) is described as

$$\mathrm{OX} = \mathrm{para}^{\min} + \mathrm{para}^{\max} - X$$

where $\mathrm{para}^{\min}$ and $\mathrm{para}^{\max}$ are the minimal and maximal of the search space.

The quasi-oppositional position may be defined as

$$\mathrm{QOX} = M + \mathrm{rand} \times (M - X)$$

4. The best NP crows among QOX are preferred as better crows and the worst crows are eliminated.
5. The positions of the crows are updated by using equation described below.

$$X^i_{\mathrm{new}} = \begin{cases} X^i_{\mathrm{old}} + r \times \mathrm{fl}^i \times \left(M^j - X^i_{\mathrm{old}}\right) & r_1 \geq \mathrm{AP} \\ \mathrm{LB} + \mathrm{rand} \times (\mathrm{UB} - \mathrm{LB}) & \text{Otherwise} \end{cases}$$

where r and $r1$ are two distinct random numbers [0, 1]. AP is the awareness probability.

6. The memory of the crows is updated with fitter crow as depicted as

$$M^i_{\mathrm{new}} = \begin{cases} X^i_{\mathrm{new}} \text{ if } f\left(X^i_{\mathrm{new}}\right) \geq f\left(M^i_{\mathrm{old}}\right) \\ M^i_{\mathrm{old}} \text{ Otherwise} \end{cases}$$

7. Steps from 4 to 10 are repeated until maximum generation reached.

5 Results and Discussion

CSA and QOCSA algorithms are endorsed to construct optimum PID, FOPID and cascade PI-FOPID controllers for two-area reheat-thermal power system with GRC. Both CSA and QOCSA algorithms are accomplished separately with 50 populations and 100 iterations for different controllers. The prime aim of CSA and QOCSA algorithms is to minimize ITAE as referred in Eq. (3). The optimal parameters of different controllers plucked by applying both CSA and QOCSA algorithms are portrayed in Table 1. The performance of CSA algorithm is enhanced by implementing oppositional-based technique. The deviations of frequency and tie-line power are illustrated in Figs. 4, 5 and 6. The system responses (settling time, undershoot and overshoot) of frequency and tie-line power divergence are portrayed in Table 2. Settling time is determined with tolerance band of 0.05%. ITAE value of

Table 1 Optimal gain parameters of different controllers optimized by CSA and QOCSA algorithms

Controllers		K_1	K_2	K_3	K_4	K_5	λ	μ
QOCSA PI-FOPID	Area-1	0.3608	0.4577	0.7563	0.0010	1.0482	0.8421	0.5666
	Area-2	0.3742	0.0769	1.1976	1.4419	0.3286	0.0970	0.3279
CSA PI-FOPID	Area-1	0.3900	0.4481	1.6216	0.0261	1.0534	0.5082	0.5680
	Area-2	0.3987	0.0686	0.9593	0.5175	0.3957	0.2358	0.2267
CSA FOPID	Area-1	1.1436	1.4284	1.5882			0.9854	0.8561
	Area-2	0.0010	0.2130	1.7503			0.9518	0.0010
CSA PID	Area-1	0.9549	0.7511	1.2417				
	Area-2	1.1655	0.9343	0.7388				

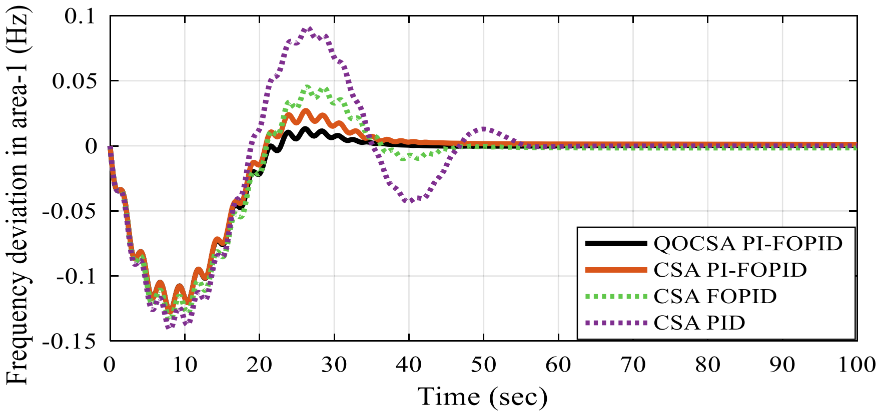

Fig. 4 Frequency deviation in area-1

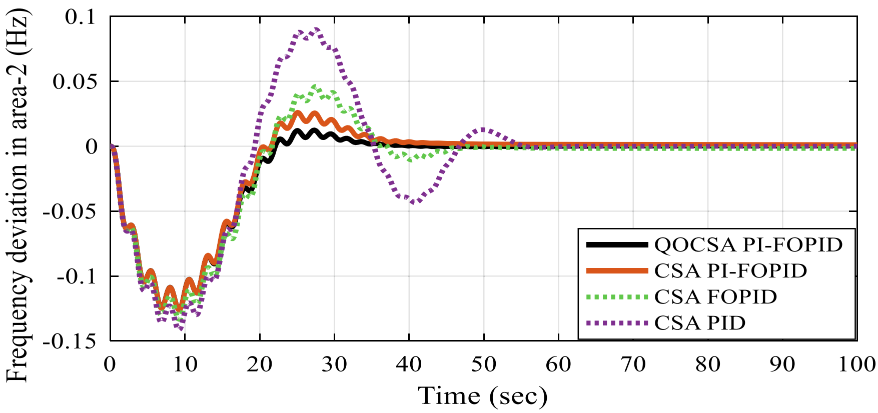

Fig. 5 Frequency deviation in area-2

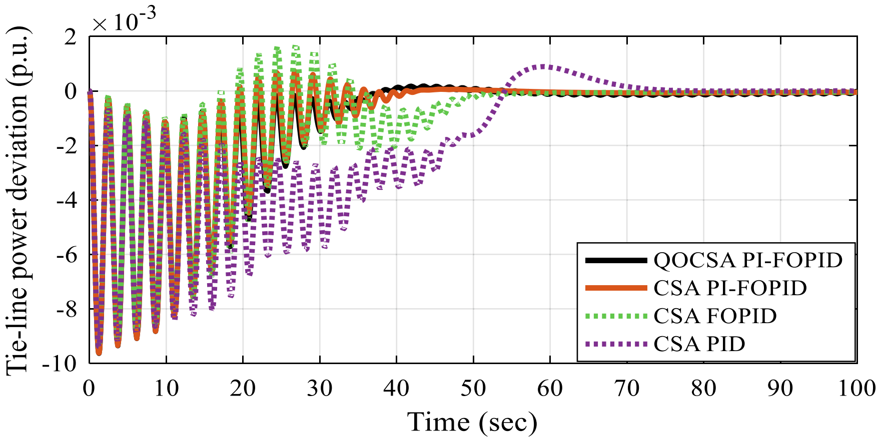

Fig. 6 Tie-line power deviation

Table 2 Performance responses of the system with different controllers optimized by QOCSA and CSA

Controllers		ΔF_1	ΔF_2	ΔP_{tie}
QOCSA PI-FOPID	$U_{sh} \times 10^{-3}$	– 140.8512	– 126.0215	– 9.6351
	$O_{sh} \times 10^{-3}$	13.2410	12.0859	0
	$T_s \times 10^{-3}$	39.82	38.51	46.04
CSA PI-FOPID	$U_{sh} \times 10^{-3}$	– 134.1248	– 126.1453	– 9.6229
	$O_{sh} \times 10^{-3}$	27.1385	26.0321	0.7271
	$T_s \times 10^{-3}$	42.49	43.06	54.58
CSA FOPID	$U_{sh} \times 10^{-3}$	– 127.6541	– 133.4574	– 9.4052
	$O_{sh} \times 10^{-3}$	45.3923	46.1386	1.7224
	$T_s \times 10^{-3}$	47.12	45.61	60.33
CSA FOPID	$U_{sh} \times 10^{-3}$	– 127.5218	– 141.3258	– 9.3921
	$O_{sh} \times 10^{-3}$	90.9874	89.9915	0.8822
	$T_s \times 10^{-3}$	55.34	54.29	73.63

the system with PID, FOPID and cascade PI-FOPID controllers optimized by CSA algorithm is 53.2453, 31.4785 and 20.0788, respectively. ITAE value of system with QOCSA algorithm optimized cascade PI-FOPID controller is 15.1248.

Figures 4, 5 and 6 and Table 2 precisely describe the suprimacy of the cascade PI-FOPID controller. Cascade PI-FOPID controller lessen the transiency (undershoot-U_{sh}, overshoot-O_{sh} and settling time T_s) and ITAE of the system.

6 Conclusion

The purpose of this paper is to validate the cascade PI-FOPID controller optimized by CSA and QOCSA algorithms as a supreme AGC for the reheat-thermal power system with GRC. For this purpose, PID and FOPID controllers are enforced separately in each area as AGC. With 1% load disturbance in area-1, cascade PI-FOPID controller optimized by CSA algorithm is validated. CSA optimized intelligent FOPID and PID controllers are validated as enhanced controllers. Further, the efficacy of the CSA algorithm is boosted by implementing quasi-oppositional technique. Finally, QOCSA algorithm optimized cascade PI-FOPID controller is substantiated with supreme performance of the system.

Appendix 1: Power System Parameters

$K_p = 120$ Hz/p.u. MW, $T_P = 20$ s, $B = 0.4249$; $R = 2.4$ Hz/p.u. MW; $T_g = 0.08$ s; $T_t = 0.3$ s;

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