A maiden application of modified grey wolf algorithm optimized cascade tilt-integral-derivative controller in load frequency control

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Abstract—Retaining area frequency to its steady-state value following load variation is one of the critical concerns in the control and operation of a multi-area interconnected power plant. This study exhibits a maiden application of cascade tilt-integral-derivative (CC-TID) controller in load frequency control (LFC) of a power system. The TID-controller is employed as a slave controller, and conventional proportional-integral (PI) controller is utilized as a master controller while designing CC-TID controller. To reveal the effectiveness of the CC-TID controller, a four-area interconnected power plant is investigated. The controller parameters are simultaneously optimized by implementing modified grey wolf optimization (mGWO) algorithm. The effectiveness of the CC-TID controller is compared with I-, PID-, PI-PD, and TID-controllers for the same test system. The comparison reveals that CC-TID yields better output compared to other controllers concerning peak overshoot, undershoot, and settling time. Moreover, the supremacy of mGWO-algorithm is confirmed over flower pollination algorithm (FPA). The system is investigated with step load and random load disturbances.

Index terms—Load frequency control; Cascade control; Tilt-integral-derivative control; Grey wolf optimization; Robustness.

I. INTRODUCTION

Load frequency control (LFC) has been practiced for a long time, and its benefits are well documented in the power system. Owing to its different amenities, the qualitative and quantitative analysis of LFC has become an attractive area of research among the researchers. LFC in power system concerned about the coordination between the real power of electrical generator and load demand. The stability of a power system is accomplished by keeping the equality within real power production and load demand plus system losses. Asynchronization of real power production and load demand leads to deviation of area frequency and tie-line power among the neighboring control areas [1]. Owing to nonlinear, higher order, and time-varying dynamics of the modern power system, restoring of frequency and tie-line power with only governor control mechanism is not satisfactory. LFC aims to continuously regulate the real output power of the synchronous machine according to randomly changing load demand. The salient features of LFC are (i) to nullify the error in frequency response, (ii) to maintain the steady flow of power through the tie-lines, and (iii) to retain synchronization among the connected generators [2].

Power system stability and control were accepted as a critical problem in the 1920s. Literature review shows that the most appreciated control theory on LFC of the power system was addressed by Chon [3] in 1954. Moreover, the application of optimal control theory in LFC was established by Elgard and Fosha [4]. Literature review unfolds that maximum of the available work in LFC area is covered by proportional-integral-derivative (PID) controller or its other variants [5-10]. However, its performance deteriorated when system complexity and nonlinearities are increased.

Furthermore, the classical feedback controller does not initiate the remedial action for the disturbances until the controlled variable deviates from the reference level. Cascade controller can be used as a substitution of a classical controller that offer better system dynamics by assigning secondary measurement and secondary feedback controller arrangement. LFC of four-area power with cascade PI-PD controller is presented in [11]. The parameters of PI-PD controller were tuned by flower pollination algorithm (FPA). Rahman et al. have presented three degree-of-freedom (3DOF) PID-controller for a three-area power system with generation rate constraint (GRC) [1]. Prakash and Sinha have applied fuzzy-neuro based intelligent PI-controller for a four-area power system [12]. However, in the case of a fuzzy logic controller, more denumerable time is needed for selecting the fuzzy rule base, and large training dataset is required to train an artificial neural network. Lately, fractional order (FO) calculus has acquired ample attention in the development of a controller for better set-point follow-up and disturbance elimination ability. Authors of [13] have incorporated the firefly algorithm (FA) optimized fractional order integral-derivative controller in a power system for solving LFC problem. 2DOF fractional-order PID controller is reported in [14]. Tilt-integral-derivative (TID) controller for two-area and three-area power system is published in [15]. However, the realization of FO controller is quite tricky compared to the integral order (IO) controller.

For exploring the efficacy of secondary controller, it is demanded to set the controller settings at optimum value and normally derived by applying optimization algorithms [1]. Several algorithms like biogeography-based optimization (BBO) [1, 16], harmony search algorithm (HSA) [2], bacteria-foraging optimization algorithm (BFOA) [5], quasi-oppositional symbiotic organism search (QOSOS) [10], differential evolution (DE) [15], cuckoo search algorithm (CSA) [17] etc. have been extensively used in LFC.

This paper uses the merits of cascade control algorithm and fractional-order calculus to design a novel controller called cascade tilt-integral-derivative (CC-TID) controller, for the first time, to appraise the performance LFC. In the realization of CC-TID controller, TID-controller is employed as ‘slave’ controller, while PI-controller serves as ‘master’ controller. A population-based metaheuristic algorithm, namely grey wolf optimization (GWO) is applied to explore optimistic outcomes of proposed CC-TID controller parameters. To acquire symmetry in exploration and exploitation, an exponentially decreasing search direction.
matrix is included in the basic GWO-algorithm. This version of GWO is called modified GWO (mGWO). Based on aforementioned discussion, the salient contributions of this work are:

- to discuss the efficacy of designed controller, an interconnected four-area reheat thermal power system is modeled by using block diagram algebra.
- to develop a novel cascade TID-controller for retaining and enhancing the stability of concerned test system.
- to explore optimum controller gains, GWO algorithm is with modified search direction matrix is implemented.
- to ascertain superiority, the competence of CC-TID controller is compared with I-, PID-, PI-PD, and TID controllers.
- to confirm tuning efficacy, obtained results of the mGWO algorithm are compared with GWO- and FPA-algorithm.
- to affirm robust performance of mGWO-tuned CC-TID controller, the test system is further assessed with random load perturbation (RLP).

II. MODELING AND METHODOLOGIES

A. Modeling of interconnected four-area power system

A system with four unequal-area reheat thermal power plant is taken to examine the performance and practicability of CC-TID controller for stability analysis. The general structure of the test system is illustrated in Fig. 1. The detail structure of same is available in [11]. An appropriate limit of the GRC of reheating thermal unit is incorporated in the model to add a degree of nonlinearity.

\[ P_1 = 2000\text{MW} \]
\[ P_2 = 4000\text{MW} \]
\[ P_3 = 8000\text{MW} \]
\[ P_4 = 16,000\text{MW} \]

Fig. 1 Schematic diagram of four-area test system

B. Cascade tilt-integral-derivative (CC-TID) controller

Cascade controller is commonly exercised in a multi-loop control system for set-point tracking and better disturbance elimination. Unlike conventional controller, cascade controller has two loops called ‘primary or inner or slave’ loop and ‘outer or secondary or master’ loop. Inner loop reacts much faster than the outer loop such that disturbance appears in the loop can be diminished before it appears other parts of the system. The merits of cascade controller over single-loop controller are documented in [18]. Fig. 2(a) illustrates a block diagram of the control system with cascade controller. The output of the overall system is calculated by using (1).

\[ C(s) = \frac{G_p(s)}{1 + G_p(s)G_{r1}(s)G_{r2}(s)G_{r3}(s)G_{r4}(s)}D(s) \]

\[ = \frac{G_p(s)}{1 + G_p(s)G_{r1}(s)G_{r2}(s)G_{r3}(s)G_{r4}(s)G_{r5}(s)G_{r6}(s)}R(s) \]

In (1), \( R(s) \) & \( D(s) \) are reference and disturbance inputs to the system, respectively; \( G_{r1}(s) \) & \( G_{r2}(s) \) are master and slave controllers, respectively.

![Cascade TID Controller Diagram](image)

A tilt integral derivative controller (TID) has an analogous structure of PID-controller except the proportional gain \( k_p \) is replaced by a block of a transfer function (T.F) \( k_s \frac{1}{s^n} \), where \( n \neq 0 \) is called ‘tilt parameter’ and chosen in between \( (2, 3) \). This structure is referred as ‘tilt controller’ [19]. It is alluded in the literature that tilt controller is more efficient to provide better performance as compared to PID-controller [19]. The purpose of applying for tilt compensation in LFC loop is to include improved feedback loop compensation, such that better and optimal responses can extract. It further helps to keep the stability of the system under external and/or internal perturbation. The general layout of TID-controller is displayed in Fig. 2(b). The T.F of TID-controller is calculated as in (3).

\[ G_{l2} = \frac{U(s)}{ACE(s)} = \frac{k_p}{s^n} + K_i + K_d \frac{sN}{s+N} \]

where \( K_i, K_d \) are integral, and derivative gains, in order; \( N \) is low-pass filter cutoff frequency. In this work, the authors have the aim to develop and apply a novel cascade TID-controller for LFC analysis. For this purpose, the TID-controller is used in the inner loop, while PI-controller acts as the master controller in the proposed structure. The settings of the controller are optimally calculated employing mGWO technique that is discussed in the ensuing section.

III. MODIFIED GREY WOLF OPTIMIZATION ALGORITHM

Grey wolf optimization (GWO) algorithm simulates social hierarchy and hunting strategies of grey wolves. Four
types of wolves namely alpha (α), beta (β), delta (δ), and omega (ω) are defined in the hierarchy to store the initial generation of wolves. Fittest outcomes are treated as α, β, and δ and these further assists ω to explore most promising search space. The motion of wolves is updated by using (3) [20].

\[
d = \mathbf{e} \cdot x_p (t) - \mathbf{r} (t)
\]

\[
x (t + 1) = x_p (t) - A \cdot d
\]

In (3), \(x_p (t)\) & \(x (t)\) indicates position of prey (optimal point) and wolf at \(t\)th-iteration, respectively; the coefficients \(a\) & \(c\) are calculated using (4) [20].

\[
A = 2 a r - a; \quad d = 2 r
\]

where \(r\) is a random numbers; \(a\) is search direction matrix. \(a\) can be calculated by using (5).

\[
a = 2 (1 - t/T) \quad a e (0, 2)
\]

where \(T\) is maximum generation count. Moreover, to avoid local optimum solution, \(a\) is exponentially decreasing from 2 to 0, which is accomplished by (6).

\[
a = 2(1 - t^2 / T^2)
\]

This modification helps GWO to improve its performance and alleviate the convergence characteristic. Finally, the locations of omega wolves are modified with knowledge of three best wolves, i.e. \(α, β,\) and \(δ\) by solving (7)-(9) [20].

\[
d_α = c_1 x_α - x; \quad d_β = c_2 x_β - x
\]

\[
d_δ = c_3 x_δ - x
\]

\[
x_1 = x - A_1 d_α; \quad x_2 = x - A_2 d_β
\]

\[
x_3 = x - A_3 d_δ
\]

\[
x (l + 1) = \frac{1}{3} (x_1 + x_2 + x_3)
\]

The proposed LFC is framed as constraint minimization problem subjected to parameter bounds. The controller settings are tuned via the minimization of integral time absolute error (ITAE) based area control error (ACE) function. Mathematically, the proposed LFC problem is defined as

\[
\text{Minimize:} J = \int_0^T |ACE| \ast t \ast dt \quad \text{where,} \quad ACE = B_i \Delta f_i + \Delta P_{area_i}
\]

\[
K_{min}^p \leq K_p \leq K_{max}^p
\]

\[
K_{min}^d \leq K_d \leq K_{max}^d
\]

\[
N_{min} \leq N \leq N_{max}
\]

\[
K_{min}^p & K_{max}^p \text{ are minimum and maximum gains of PID-controller; } n_{min} & n_{max} \text{ are minimum and maximum value of tilt parameter; } N_{min} & N_{max} \text{ are minimum and maximum value of filter cut-off frequency. The TID- and PI-controller gains are optimally tuned within (0,1), while filter gain is selected between (0,200). For fine tuning, the input parameters of GWO are: population size = 40; generation count = 100; and elite solution = 4.}

\section{IV. IMPLEMENTATION OF MGWO FOR TUNING OF CONTROLLER GAINS}

The optimum gains of proposed CC-TID controller are derived employing mGWO algorithm. The following steps are performed while optimizing CC-TID controller parameters.

Step 1 Randomly initializes the search agents, i.e., wolves within the considered search area. This process is analogous to the initialization controller gains.

Step 2 Calculate minimum ACE value employing (10). Arrange the solution from best to worst as per the calculated minimum ACE value.

Step 3 Modify the position of search agents (controller gains) employing (11).

\[
\text{for } k = 1: n_p
\]

\[
\text{if } \min (ACE) < \alpha
\]

\[
\alpha \leftarrow \text{value} \min (ACE)
\]

\[
\text{end}
\]

\[
\text{if } \min (ACE) > \alpha \& \& \min (ACE) < \beta
\]

\[
\beta \leftarrow \text{value} \min (ACE)
\]

\[
\text{end}
\]

\[
\text{if } \min (ACE) > \alpha \& \& \min (ACE) > \beta \& \& \min (ACE) < \delta
\]

\[
\delta \leftarrow \text{value} \min (ACE)
\]

\[
\text{end}
\]

Step 4 Decrease the search direction matrix by using (6).

Step 5 Update the position of wolves including omega by using (7)-(9).

Step 6 Check whether any solution goes out of the search area or not.

Step 7 Go to Step 3 unless the maximum iteration count is fulfilled.

\section{V. RESULTS AND DISCUSSION}

The competence of proposed mGWO-tuned CC-TID controller is assessed on four-area interconnected power system following 1% step load perturbation (SLP) in area-1. The proposed mGWO-algorithm is employed for fine tuning of CC-TID controller gains. The optimized values of CC-TID controller with mGWO-algorithm are: slave controller-

\[
K_{p3} = 0.3740, \quad K_{I1} = 0.9841, \quad K_{I1} = 0.2918, \quad K_{p2} = 0.9601, \quad K_{d2} = 0.0215, \quad K_{d2} = 0.1830, \quad K_{p3} = 0.0663, \quad K_{d3} = 0.8938, \quad K_{d3} = 0.2620, \quad K_{p4} = 0.8230, \quad K_{p4} = 0.9279, \quad K_{d4} = 0.0855, \quad N_{1} = 18.7314, \quad N_{2} = 8.0189, \quad N_{3} = 3.8000, \quad N_{4} = 2.7474, \quad n_{1} = 2.6825, \quad n_{2} = 2.6454, \quad n_{3} = 2.9650, \quad n_{4} = 2.9513, \quad \text{master controller-}
\]
$K_p = 0.9643$, $K_i = 0.9903$, $K_d = 0.0056$, $K_{p_1} = 0.0105$, $K_{p_2} = 0.7258$, $K_{p_3} = 0.8691$, $K_{p_4} = 0.1932$, $K_{i_1} = 0.9695$. For showing adeptness of mGWO-algorithm, test system is further simulated with basic GWO-algorithm. The controller settings after optimization are slave controller- $K_{p_1} = 0.4061$, $K_{i_1} = 0.9975$, $K_{d_1} = 0.2795$, $K_{p_2} = 0.9690$, $K_{i_2} = 0.0469$, $K_{d_2} = 0.0174$, $K_{p_3} = 0.0588$, $K_{i_3} = 0.9182$, $K_{d_3} = 0.3786$, $K_{p_4} = 0.7563$, $K_{i_4} = 0.9399$, $K_{d_4} = 0.3579$, $N_1 = 9.1960$, $N_2 = 5.9854$, $N_3 = 21.9895$, $N_4 = 8.7048$, $n_1 = 2.8199$, $n_2 = 2.6180$, $n_3 = 2.4027$, $n_4 = 2.9197$, master controller- $K_{p_1} = 0.4061$, $K_{i_1} = 0.9975$, $K_{d_1} = 0.9690$, $K_{p_2} = 0.0469$, $K_{i_2} = 0.0588$, $K_{d_2} = 0.9182$, $K_{p_4} = 0.7563$, $K_{i_4} = 0.9388$.

![Fig. 3 Convergence profile of proposed algorithm with CC-TID controller](image)

The minimum ACE computed with the GWO and mGWO algorithms is $J = 0.0283$ and $J = 0.0268$, respectively. The convergence characteristic of mGWO-algorithm with optimized CC-TID controller is illustrated in Fig. 3. For comparison, convergence profile of the basic GWO-algorithm also draws in the same figure. Fig. 3 reveals that the mGWO is capable of exploring more probable global solutions compared to GWO. It is further viewed from Fig. 3 that mGWO algorithm exhibits least minimum ACE than that calculated by GWO algorithm. The fitness value with mGWO algorithm is improved by 5.3%.

The system outputs with optimized CC-TID controllers are obtained and compared in Fig. 4. Figs. 5-6 illustrate the profiles of optimized controller variables with iterations. The transient response specifications such as rise time (RT), peak time (PT), overshoot (OS), undershoot (US), and settling time (ST) are calculated and listed in Table 1. It is obvious from Fig. 4 that mGWO: CC-TID controller improves damping of frequency and power oscillations as compare to FPA- and GWO-optimized controllers. It is further elicited from Table 1 that mGWO: CC-TID controller offer least value ST, OS, and US of frequency and tie-line power oscillations than other controllers shown in Fig. 4. Hence it may conclude that mGWO: CC-TID controller outperforms GWO: CC-TID, FPA: PI-PD, FPA: PID and FPA: I controllers. Only four figures are shown to validate the above statement.

To test the performance of mGWO: CC-TID controller against unswerving load variation, a time-varying SLP (TVSLP) as shown in Fig. 7 is projected to area-1. The applied TVSLP is also defined for different magnitude. To confirm robustness, the controller designed at nominal condition is considered for the study. The error in system output following TVSLP is displayed in Fig. 7. Fig. 7 confirms the robustness and superiority of mGWO: CC-TID controller over other optimized controllers considered in this work concerning OS, US, ST, and numbers of oscillation.

![Fig. 4 Transient behavior of test system](image)
power is computed by solving (11) and plotted in Fig. 9. The probability density of frequency and tie-line controller for frequency control is also affirmed from Fig. 8(b). The superiority of the CC-TID controller is immensely handled the applied RLP, high peak undershoots. Fig. 8(b) illustrates that mGWO: CC-TID controller offer sluggish output with applied RLP, painted and compared in Fig. 8(b). It is evident from Fig. 8(a) that FPA: PI-PD controller offer sluggish output with high peak undershoots. Furthermore, a random load perturbation (RLP) with mean and variance of 0.8506 and 0.0015, respectively, is applied to area-1 for appraising the performance of mGWO: CC-TID controller. The projected RLP profile is displayed in Fig. 8(a). The frequency error of area-1 is mean and variance of 0.8506 and 0.0015, respectively, is displayed in Fig. 8(a). The frequency error of area-1 is mean and variance of 0.8506 and 0.0015, respectively, is displayed in Fig. 8(a). The frequency error of area-1, (b) tie-line power variation among area-1. (a) and 2 (b)

\[ f(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2 \right] \]  

Fig. 5 mGWO-optimized CC-TID slave controller gains

where \( \sigma, x, \& \mu \) are standard deviation, samples of frequency or tie-line power, and mean, respectively.

Fig. 6 mGWO-optimized CC-TID master controller gains (area-1 and 2)

Furthermore, a random load perturbation (RLP) with mean and variance of 0.8506 and 0.0015, respectively, is applied to area-1 for appraising the performance of mGWO: CC-TID controller. The projected RLP profile is displayed in Fig. 8(a). The frequency error of area-1 is mean and variance of 0.8506 and 0.0015, respectively, is displayed in Fig. 8(a). The frequency error of area-1, (b) tie-line power variation among area-1. (a) and 2 (b)

![Fig. 5 mGWO-optimized CC-TID slave controller gains](image1)

![Fig. 6 mGWO-optimized CC-TID master controller gains (area-1 and 2)](image2)

![Fig. 7 Transient performance of test system following to TVSLP (a) frequency variation of area-1, (b) tie-line power variation among area-1 and 2](image3)
A novel controller, namely CC-TID in LFC of a four-area power system for frequency and tie-line power control is discussed. The mGWO algorithm is applied for tuning of CC-TID parameters. Critical observations of the presented results confirm that mGWO: CC-TID provides lowest minimum error function, improved time response over GWO and FPA based controllers. The predominance and robust performance of mGWO algorithm optimized CC-TID controller is further confirmed with TVSLP and RLP.

VI. CONCLUSION

A novel controller, namely CC-TID in LFC of a four-area power system for frequency and tie-line power control is discussed. The mGWO algorithm is applied for tuning of CC-TID parameters. Critical observations of the presented results confirm that mGWO: CC-TID provides lowest minimum error function, improved time response over GWO and FPA based controllers. The predominance and robust performance of mGWO algorithm optimized CC-TID controller is further confirmed with TVSLP and RLP.

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