A hybrid MFO-GHNN tuned self-adaptive FOPID controller for ALFC of renewable energy integrated hybrid power system

Rajeswari Ramachandran | Jeevitha Satheesh Kumar | Balasubramonian Madasamy | Veerapandiyan Veerasamy

1 Department of Electrical Engineering, Government College of Technology, Coimbatore, India
2 Department of Electrical Engineering, Alagappa Chettiar College of Engineering and Technology, Karaikudi, India
3 Advanced Lightning, Power and Energy Research (ALPER), Department of Electrical and Electronics Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), Selangor, Malaysia

Abstract

This paper proposes a hybrid moth flame optimization–generalized Hopfield neural network (MFO-GHNN) optimized self-adaptive fractional order proportional integral derivative (FOPID) controller for automatic load frequency control of multi-area hybrid power system (HPS). The control problem is formulated with an objective function of area control error associated with unknown parameters such as $K_p$, $K_i$, $K_d$, $\lambda$ and $\mu$ of FOPID controller. The fractional order of differentiator and integrator terms, and the initial values of $K_p$, $K_i$ and $K_d$ are drawn from MFO algorithm. Then, the $K_p$, $K_i$ and $K_d$ are fine-tuned by solving the dynamic equations governing the behaviour of GHNN under system uncertainties. To test the practicability and effectiveness of the proposed controller, the multi-area HPS is studied with uncertain change in load demand, system parameters, solar and wind power generation. The proposed method is modelled using MATLAB/Simulink. The results showed that the steady state and transient performance indices of proposed FOPID controller are significantly enhanced than the PID, MFO-FOPID and GHNN-PID controllers. In addition, the stability of non-linear dynamic HPS is analysed using Matignon’s theorem of stability. Further, the performance of controller is validated using real time digital simulator run in hardware-in-the-loop environment.

1 INTRODUCTION

Nowadays, the complexity of electric power system (PS) increases due to the deregulation of system, integration of renewable energy (RE) sources, uncertainties in power generation, loading and system parameters leading to frequency instability. This problem is overcome by the automatic generation control (AGC) which plays a significant role in modern PS by controlling area control error (ACE) of interconnected system. For secured and reliable operation of dynamic PS, the frequency oscillation must be within tolerable limits of $\pm 5\%$ originated from sudden perturbations of load or generation [1–3].

Over the years, many researchers have proposed numerous classical and intelligence-based control strategies to maintain the system frequency and tie line power flow variation. However, the rapid growth of PS requires faster solution, i.e. controller with faster steady state, transient performance and high degree of reliability. In addition, the type and design of controller is a major factor which influences the performance and stability of the system remarkably. The conventional integer controller such as Ziegler and Nichols (Z–N) tuned proportional integral derivative (PID) may be inept to operate in wider range for handling sudden change in system parameters and load variation in the PS [3]. On the flipside, many robust control strategies such as sliding mode control (SMC) and second order SMC, Teaching–learning-based optimization tuned SMC, distributed model predictive control; $H_2/H_{\infty}$ and also model free control strategy have been used for ALFC application. The control law of these controllers is designed regardless of system uncertainties and disturbances [4–8]. Thus, implementation of robust controllers is a tedious process for real time application. Therefore, the conventional classical proportional integral (PI) and PID controller were widely used to reduce the computational complexity of the controller. However, tuning the gain values of...
the controller is a critical task for the system involving large non-linearities. As a result, researchers have optimized gain values of the controller by various artificial intelligence (AI) techniques such as bat inspired algorithm [9], adaptive neural network (NN) [10, 11], firefly algorithm [12], cluster based multi-objective optimization [13], differential search [14], MFO [15], and cuckoo optimized fuzzy tuned PID controller [16] for ALFC application.

On the other hand, the fractional order PID (FOPID) controller is more significant than the PI/PID controller. As it gives more flexibility to design the control system for adjusting PS dynamics involved in ALFC application. Since this controller has more tuning freedom and wider region of parameters that stabilize the plant under control, and offers improvement in control loop robustness with minimum control effort. Hence, it ascertainment the superior quality of system response than the integer order controller such as PI/PID [17]. The FOPID controller has more scope in AGC operation in concurrence with the computational intelligence (CI) techniques due to above mentioned properties. Therefore, researchers have used PSO, artificial bee colony and imperialist competitive algorithm and so on to tune the FOPID controller parameters for multi-area ALFC application [17–19]. Nevertheless, the work presented in the literature fails to consider the system non-linearities such as generator rate constraints (GRC), governor dead band (GDB) and boiler dynamics all together with RE sources such as solar thermal power and wind power generation, energy storage system such as aqua electrolyser (AE) and fuel cell (FC) for load frequency control.

On the flipside among various AI based control strategies, the NN based method offers the self-adaptive property to handle system uncertainties than the CI algorithm as it requires the gain values need to be retuned for wide change in system parameters [10, 11]. Conversely, the feed forward NN requires a voluminous set of training data and its accuracy also degrades for the system having large uncertainties due to its unidirectional data flow. Consequently, a single layer gradient type recurrent neural network called ‘GHNN’ has been widely used for solving various engineering problems due to the interesting properties of content accessible memory, robustness, adaptiveness and less computational effect [20, 21]. However, it suffers from the limitation of trapping into local minima for some of the optimization problems [21]. The concept of gradient is inapplicable for design of fractional orders in FOPID controller. Therefore, a maiden attempt has been made by combining the deterministic, robust and self-adaptive property of recurrent based GHNN with the stochastic global optimization method of moth flame optimization. Thus MFO is used to tune the fractional orders (λ and μ), and obtain the initial values of (Kp, Ki and Kd) of FOPID controller by solving the neuro-dynamic equation of GHNN which gives the self-adaptive property of designed controller. Also, the problem of reaching local minima is resolved through initial tuning of GHNN using MFO algorithm to reach global minima.

Recently, the authors in the previous studies have proposed GHNN based self-adaptive PID controller for controlling the frequency of multi-area thermal PS. The results obtained reveal that the designed PID controller response to sudden change in system parameters and loading [11]. However, in this presented work the dynamic equation of energy function with respect to gain values (Kp, Ki and Kd) of FOPID controller describing the behaviour of GHNN and fractional terms of λ and μ are tuned using MFO algorithm. This is obtained by minimizing the sum of integral absolute error (IAE) and integral time absolute error (ITAE) of ACE of multi-area hybrid power system (HPS). Furthermore, the stability of interconnected system is another major concern for power utilities to maintain the frequency stability of system for wide change in system parameters and loading. Nonetheless, in the literature the authors study the stability of interconnected system for tuned fractional order controllers (FOC). Consequently, this paper also proposes a method to analyse the frequency stability of system in addition to regulating the frequency and tie-line power of the system using Matignon’s stability theorem of fractional orders. The main contributions of this paper are as follows:

a. To design a robust self-adaptive MFO-GHNN tuned FOPID controller for ALFC of multi-area HPS.

b. To validate the designed controller for various system uncertainties such as change in loading, inertia and step load perturbation (SLP) of the system.

c. To compare the effectiveness of MFO-GHNN based FOPID controller with Z-N PID, GHNN PID and MFO FOPID controller.

d. To derive the transfer function and analyse the stability of HPS with FOPID controller using Matignon’s theorem.

This paper is structured as follows: Section 2 presents the multi-area model of interconnected HPS with non-linearities. Section 3 portrays the design and analysis of proposed controller. The results and discussion are explained with its closed loop stability analysis of the system in Sections 4 and 5 respectively. The hardware implementation validating the proposed controller is presented in Section 6. The conclusion and future scope of the work is presented in Section 7.

2 | POWER SYSTEM MODEL

The general nth area dynamic interconnected HPS model is shown in Figure 1 including rehear turbine, boiler dynamics and the system with non-linearities such as GRC and GDB with integration of RE sources. This system is extensively used in literature and the parameters associated with this HPS are given in [22]. The HPS consists of RE sources such as solar thermal, wind power generation and energy storage system of AE and FC.

2.1 | Solar thermal power generation

The solar power is abundantly available renewable source compared to all other resources. The solar thermal power generation (STPG) has been extensively used in hybrid with fossil fuel
and wind power sources etc., for operating the grid with power balance condition [22]. For small-signal analysis, the STPG system can be linearized with few approximations and the transfer function is defined by combination of solar collector and steam turbine generator as [22, 23],

\[ G(s) = \frac{K_s}{1 + sT_s} \frac{K_T}{1 + sT_T} = \frac{\Delta P_{STPG}}{\Delta P_{solar}} \] (1)

where \( K_s \) and \( K_T \) represents the gain constant, \( T_s \) and \( T_T \) represents the time constant of solar collector and steam turbine, respectively. In this work, two units of STPG with plant capacity of 3 MW each are considered.

2.2 Wind turbine power generation

For small-signal analysis, the dynamics associated with the wind turbine power generation (WTPG) can be modelled by the first order transfer function as [22, 23],

\[ G_{WTG}(s) = \frac{K_{WTG}}{1 + sT_{WTG}} = \frac{\Delta P_{WTPG}}{\Delta P_{wind}} \] (2)

\[ G_{AE}(s) = \frac{K_{AE}}{1 + sT_{AE}} \]

\[ G_{AE}(s) = \frac{\Delta P_{AE}}{(\Delta P_{WTG} + \Delta P_{STG}) (1 - K_s)} \] (4)

where, \( K_{AE} = \frac{P_t}{P_{WTG} + P_{STG}} \) and is assumed as 0.6, \( K_{AE} \) and \( T_{AE} \) are the gain and time constant of AE, respectively.

\[ G_{FC}(s) = \frac{K_{FC}}{1 + sT_{FC}} \]

where \( K_{FC} \) and \( T_{FC} \) are gain constant and time constant of FC, respectively.

3 DESIGN OF FOPID CONTROLLER

FOPID controller is extensively used in most of the research work for industrial applications [3]. FOC deals with the concept of differential equations derived from fractional order calculus. Over the years, the order of differentiation/integration are real numbers and in last few decades the FOC plays a vital role in control engineering domains such as process control, nuclear reactor control and robotics. Inspired by these, a maiden attempt of FOPID for ALFC application is witnessed largely in literature work leading to considerable benefits in
terms of modelling accuracy and flexibility in controller design. Integral–differential definitions of FOPID are analysed in [18, 19]. The FOPID controller transfer function in s-domain is given as,

\[ C(s) = \frac{E(s)}{U(s)} = K_p + K_i s^{-\lambda} + K_d s^\mu \]  

(6)

where \( K_p, K_i \) and \( K_d \) are the controller gains; \( \lambda, \mu \) are fractional orders of integral and differential operators, which are tuned for stabilizing the plant such that \( \lambda, \mu > 0 \). In this work, the fractional orders are tuned using MFO and the gain constants are adjusted by GHNN approach which enhances the property of self-adaptiveness of the system.

3.1 Closed loop control

The closed loop control of multi-area HPS with FOPID controller tuned through intelligent algorithm is shown in Figure 2, where, \( Y_{\text{ref}} \) is the set value of the plant, \( Y_{\text{plant}} \) is the actual output of the plant, such that \( Y_{\text{plant}} = T \{ u(t) \} \) and \( T \) is the transformation operation performed by the system on \( u(t) \) to give the output \( Y_{\text{plant}} \). The output of the FOPID controller of closed loop system is as follows,

\[ e(t) = K_p AC_E + K_i \int_0^t AC_E d\tau + K_d \frac{d^\mu AC_E}{d\tau} \]  

(7)

In this work, the gain parameters are tuned using GHNN by minimizing absolute values of ACE. The fractional orders of \( \lambda \) and \( \mu \) are derived by minimizing the objective function which is obtained from IAE and ITAE as given below,

\[ J_1 = IAE = \int_0^t |e(\tau)| d\tau \]  

(8)

\[ J_2 = ITAE = \int_0^t \{ e(\tau) \} \tau d\tau \]  

(9)

Thus, the objective function for tuning the parameters of FOPID controller is given by,

\[ \text{Min. } f(\lambda, \mu) = \text{Min. } (J_1 + J_2) \]  

(10)

Subjected to the following inequality constraints:

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

\[ K_{i\min} \leq K_i \leq K_{i\max} \]

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

\[ \lambda_{\min} \leq \lambda_i \leq \lambda_{\max} \]

\[ \mu_{\min} \leq \mu_i \leq \mu_{\max} \]

The minimum and maximum limits are taken between 0 and 1.

3.2 MFO-GHNN based controller strategy

This section describes the MFO based GHNN optimization for tuning the gain and fractional terms of FOPID controller for ALFC application of interconnected multi-area HPS. The forthcoming subsection details GHNN and MFO as follows:

3.2.1 Mapping of GHNN to FOPID parameters

Generalized Hopfield neural network is a time varying recurrent neural network with dynamical associated memory. The behaviour of network is characterized by Lyapunov function framed from ACE of interconnected system and minimizing the error in obtaining the gain values of controller. The detailed explanation on general framework of GHNN based self-adaptive PID is presented in the previous work [11]. The steps for tuning the FOPID controller are detailed as follows:

\textit{Step-1: Energy function:} Formulate the error function to be minimized as Lyapunov energy function that governs the behaviour of GHNN for tuning the gain parameters of FOPID controller as given below,

\[ E(K_p, K_i, K_d) = \frac{1}{2} e(t)^2 \]  

(11)

From Figure 2 (11) can be expressed as,

\[ E(K_p, K_i, K_d) = \frac{1}{2} (j_{\text{ref}} - j_{\text{plant}})^2 \]  

(12)
\[ y_{\text{ref}} \] being the reference value of the plant output, \( y_{\text{plant}} \) is the current output of the plant, i.e., \( y_{\text{plant}} = T(u(t)) \), where \( u(t) \) is the output of the controller and defined as,

\[
u(t) = K_p e(t) + K_i \int e(t) \, dt + K_d \frac{d^2 e(t)}{dt^2} \quad (13)
\]

Min. \( E \) (\( K_p, K_i, K_d \))

\[
e = \frac{1}{2} \left( y_{\text{ref}} - T \left[ K_p e(t) + K_i \int e(t) \, dt + K_d \frac{d^2 e(t)}{dt^2} \right] \right)^2 \quad (14)
\]

**Step-2:** Dynamics of GHNN: Differentiate the energy function (14) with respect to the unknown variables to be determined. The parameters namely \( K_p, K_i \) and \( K_d \) are considered as variable, and fractional orders remaining constant as the differential operator with fractional order cannot be differentiated. The differential equations that represent the dynamics of each neuron with respect to the variables \( K_p, K_i \) and \( K_d \) are,

\[
\frac{dK_p}{dt} = -\frac{\partial E}{\partial K_p} \quad (15)
\]

\[
\frac{dK_i}{dt} = -\frac{\partial E}{\partial K_i} \quad (16)
\]

\[
\frac{dK_d}{dt} = -\frac{\partial E}{\partial K_d} \quad (17)
\]

The dynamical equations represent that the dynamics associated with the NN reduces to zero in the negative gradient direction. The RHS of Equations (15)–(17) are derived from (14) and obtained the following update rules of neuron such as \( K_p, K_i \) and \( K_d \) are represented as [13, 24],

\[
\frac{dK_p}{dt} = e(t) T'(u(t)) e(t) \quad (18)
\]

\[
\frac{dK_i}{dt} = e(t) T''(u(t)) D_{3}^{\lambda} e(t) \quad (19)
\]

\[
\frac{dK_d}{dt} = e(t) T''(u(t)) D_{3}^{\mu} e(t) \quad (20)
\]

where \( D \) is the differential operator

**Step-3:** Activation function: The dynamics of the neuron are input to the activation function. The linear activation function is considered and in general is defined as [13, 24]

\[
\begin{bmatrix}
x_p \\
x_i \\
x_d \\
\end{bmatrix} = \begin{bmatrix}
K_p \\
K_i \\
K_d \\
\end{bmatrix} \begin{bmatrix}
\Phi(u_1) \\
\Phi(u_2) \\
\Phi(u_3) \\
\end{bmatrix} \quad (21)
\]

where the components of \( u \) representing the dynamics of each neuron. Thus \( K_p = \Phi(u_1), K_i = \Phi(u_2), K_d = \Phi(u_3) \), where \( x_p, x_i \) and \( x_d \) are the input neurons of the recurrent network. The activation function of the neuron is \( \Phi \) and \( \Phi(u) : \mathbb{R} \rightarrow [0, 1] \). Thus, the architecture of GHNN based FOPID controller is represented in Figure 3

**Step-4:** Fractional order coefficients (\( \lambda \) and \( \mu \)): The coefficients are considered constant as the differential operator with fractional order cannot be calculated. Therefore, the dynamical equations are not obtained for \( \lambda \) and \( \mu \). CI techniques based MFO algorithm has been used for tuning the parameters \( \lambda \) and \( \mu \) of GHNN based FOPID controller by solving (18)–(20). The following sub section details the step by step procedure of MFO algorithm.

### 3.2.2 MFO-GHNN tuned FOPID controller

This section describes the tuning of dynamic equation of GHNN and fractional orders of FOPID controller by minimizing (10) using MFO algorithm and the steps are detailed as follows [15, 25]:

**Step-1:** Initialize the gain and fractional order terms, number of moths (\( n \)) and the problem variables (\( d \)) that represent the position of moths in the search space. The set of moths in the form of matrix is given as

\[
M = \begin{bmatrix}
m_{1,1} & m_{1,2} & \cdots & m_{1,d} \\
\vdots & \vdots & \ddots & \vdots \\
m_{n,1} & m_{n,2} & \cdots & m_{n,d} \\
\end{bmatrix} \quad (22)
\]

**Step-2:** Compute the fitness function (10) and obtain the fractional terms, and gain terms by solving the dynamic...
equation of GHNN (18)–(20) of FOPID controller. Arrange the obtained optimal values of fitness function of each moth (OM) as in (22) and store the corresponding fitness values as follows,

$$OM = \begin{bmatrix} OM_1 \\ OM_2 \\ \vdots \\ OM_n \end{bmatrix}$$

(23)

Step-3: Define the global best key components flames (F) as like moth with same size of matrix as in (22) and store the corresponding fitness value of each flames in an array as that of step-2 called optimal flames (OF). The moth is the search agent which search within the search space and the best position of moth is called as flame or flag.

Step-4: The algorithm starts with initialization of population of moth randomly and computing the corresponding fitness value and updated for the objective function minimization through the movement of moth in search space. The optimized results are obtained with the satisfaction of termination criteria.

Step-5: The mathematical model that governs the behaviour of transverse orientation (movement) of moth ($M_i$) and its position is updated with respect to flame ($F_j$) using the spiral function ($S$) as

$$M_i = S(M_i, F_j)$$

(24)

Step-6: The logarithmic spiral function is defined as follows:

$$S \left( M_i, F_j \right) = D_i e^b \cos \left( 2\pi t \right) + F_j$$

(25)

where $D_i$ denotes the distance between the $i$th moth and $j$th flames given in Figure 4, $b$ is a real constant describing the logarithmic spiral shape and $t$ is the random number varies between $-1$ and $1$ respectively. Thus the best optimal solution can be obtained by proper selection of $t$ if $t = 1$ the distance $D$ is larger and $t = -1$ the distance between moth and flame is minimum. So the variation in $t$ decreases linearly from 1 to $-1$ leads to movement of moth in search region and each moth update its position with only one flame. The best solution is considered as flame and its value changes at every iteration and the moth need to update its value with new flame. The number of flame decreases as the number of iteration decreases and the final flame is the optimal solution. The relation describing this generalized statement is given as below,

Number of Flames$_{L,th~iteration} = \text{round} \left( (N - L) \ast \frac{N - 1}{T} \right)$$

(26)

where $N$ is the initial number of flames, $L$ is the current iteration, and $T$ is the maximum number of iterations. The initialization of parameters is referred from [15].

Step-7: Check the tolerance ($\tau$) is within the specified range of 0.0001, and then obtain the tuned values of fractional orders and initial gain values of GHNN such as $K_p$, $K_i$ and $K_d$ through minimization of (10). Else, repeat the step from (2) to (7) until convergence is reached. The MFO-GHNN tuned FOPID controller possesses the self-adaptive property by the dynamic behaviour of GHNN. The robustness of the MFO-GHNN controller is tested on multi-area HPS and compared with MFO tuned FOPID, GHNN PID and Z-N tuned PID controller. The gain values obtained from these methods are as follows: MFO-GHNN tuned FOPID: $K_p = 0.00014, K_i = 0.01229, K_d = -2.786 \times 10^{-8}, \lambda = 0.67458$ and $\mu = 0.001487$, MFO FOPID: $K_p = 0.35, K_i = -0.3006, K_d = -0.991, \lambda = 0.94$ and $\mu = 0.6$; GHNN-PID: $K_p = -0.9075, K_i = -0.3012, K_d = 0.1501$ and Z-N PID: $K_p = 0.2284, K_i = 0.2709, K_d = 0.4452$.

4 | SIMULATION RESULTS AND DISCUSSION

The application of proffered MFO-GHNN tuned FOPID controller for multi-area HPS is developed and simulated for different cases in Matlab/Simulink and the results are validated using real-time digital simulator (RTDS) run in hardware-in-the-loop (HIL).

4.1 | Case I-A: Thermal power system

In this case, a reheat thermal system associated with boiler dynamics without RE sources is studied. The load demand in area-1 is remain unperturbed with increase in the step load change of 1.25% in area-2 and also 50% change in the inertia constant of multi-area thermal PS have been considered.
TABLE 1  Performance indices of two-area HPS for various controllers

| Cases | Performance Indices | Δf | ΔP | |
|-------|---------------------|----|----|-----|
|       | PID | MFO-FOPID | GHNN PID | MFO-GHNN FOPID | PID | MFO-FOPID | GHNN PID | MFO-GHNN FOPID |
| I-A   | IAE | 0.1069 | 0.1227 | 0.0712 | 0.0203 | 0.1338 | 0.1175 | 0.0746 | 0.0214 |
|       | ITAE | 0.4933 | 0.6391 | 0.307 | 0.0996 | 0.6942 | 0.5156 | 0.3205 | 0.0886 |
|       | ISE | 0.0021 | 0.0017 | 0.0008 | 0.0001 | 0.0019 | 0.0022 | 0.0009 | 0.0001 |
|       | ITSE | 0.0046 | 0.0054 | 0.0018 | 0.0001 | 0.0052 | 0.0042 | 0.0015 | 0.0001 |
|       | CE | 0.118 | 0.108 | 0.0961 | 0.0721 | 0.124 | 0.1187 | 0.1096 | 0.0756 |
|       | ST (s) | 21.48 | 20.09 | 10.51 | 7.701 | 22.53 | 20.63 | 10.816 | 6.26 |
|       | SE (×10^-4) | 4.2781 | 2.5852 | 2.1581 | 0.0081 | 0.16 | 0.126 | 0.016 | 0.0155 |
|       | | 0.0413 | 0.0253 | 0.0247 | 0.0108 | 0.0367 | 0.0272 | 0.0266 | 0.0174 |
| II-A  | IAE | 0.1046 | 0.1021 | 0.03459 | 0.03325 | 0.116 | 0.1028 | 0.04848 | 0.04115 |
|       | ITAE | 0.8154 | 0.416 | 0.1213 | 0.0385 | 0.8267 | 0.4879 | 0.1836 | 0.04769 |
|       | ISE | 0.0013 | 0.0006 | 0.0004 | 0.0001 | 0.0014 | 0.0009 | 0.0005 | 0.0002 |
|       | ITSE | 0.0039 | 0.0016 | 0.0006 | 0.0004 | 0.0038 | 0.0019 | 0.0006 | 0.0005 |
|       | CE | 0.0063 | 0.0063 | 0.0063 | 0.0043 | 0.0107 | 0.0107 | 0.0105 | 0.0102 |
|       | ST (s) | 28.1 | 19.59 | 11.19 | 9.22 | 28.05 | 14.94 | 13.5 | 8.72 |
|       | SE (×10^-5) | 0.0059 | 0.0061 | 0.0038 | 0.0026 | 0.0025 | 0.0068 | 0.0037 | 0.0025 |
|       | | 0.0329 | 0.0209 | 0.0205 | 0.0112 | 0.0330 | 0.0258 | 0.0226 | 0.0195 |

*CE-control effort, ST-settling time, SE-steady-state error, |P–O| - magnitude of peak overshoot.

FIGURE 5  Dynamic response of two-area thermal power system (case I-A)

The change in frequency and tie-line power of both areas are observed and shown in Figure 5. It is inferred from the plot, the oscillations in the system frequency and tie-line power deviations are damped out quickly by the proposed controller than other controllers. To prove the effectiveness of the controller, the steady state indices such as IAE, ITAE, integral square error (ISE) and integral time square error (ITSE) and transient performance indices such as settling time (ST) and peak overshoots magnitude (P-O), steady state error (SE) and control effort are also evaluated and tabulated in Table 1. The results show that the proffered controller outperforms than PID, GHNN PID and MFO tuned FOPID controllers.

4.2  | Case II-A: Hybrid power system

In this case, the two-area system comprises of reheat-thermal, solar thermal and wind power generation with energy storage system such as AE and FC was considered with increase in load demand. A sudden increase in load demand of area-2 (ΔP_{D2}) equal to 1.25% of system plant capacity have been applied with area-1 remain undisturbed to HPS. The total power generation of two-area interconnected HPS is given as follows,

$$P_g = P_{\text{Thermal}} + P_{\text{Solar}} + P_{\text{Wind}} - P_{\text{AE}} + P_{\text{FC}}$$  \hspace{1cm} (27)

The dynamic responses such as system frequency and tie-line power oscillations are settled down quickly to steady state with minimum settling time by the proposed GHNN-FOPID controller than other controllers as illustrated in Figure 6. Moreover, the steady state and transient performance indices such as SE, ST and P-O, IAE, ITAE, ISE and ITSE respectively, and control effort (CE) are significantly improved for the suggested FOPID controller than other controllers as given in Table 1. The
effectiveness of the controller is tested by addition of RE sources abruptly into the thermal system. Initially, the thermal system was considered to supply the load demand from 0 to 30 s, at 30 s two units of STPG with plant capacity of 3 MW each was switched, at 60 s three units of WTPG with plant capacity of 2 MW was added for supplying the load demand of the system.

The frequency and tie-line power variation for these unexpected changes in power generation were recorded and illustrated in Figure 7. It is observed that the frequency and tie-line power oscillate initially and settle to steady state rapidly by the proposed controller and the same inference is seen for addition of solar and wind power generation into the system without any oscillations in the response. However, the increase in total power generation is observed by the overshoots in response and this is minimized rapidly by the proposed robust self-adaptive controller than other controllers. Also, the effect of change in RE sources into the system is balanced by the energy storage system that results in minimum overshoots in tie-line of interconnected HPS.

4.3 Feasibility analysis of proposed controller

In this section, the performance of proposed controller is validated for self-adaptiveness, sensitivity and its applicability to real-time system. Further, the comparative analysis was made with other optimization techniques for tuning of controller parameters. These are considered as different cases and described as follows:

4.4 Case-1: Self-adaptiveness of the controller

The self-adaptiveness of the propounded controller is validated by applying sudden change in the step load demand of 0.7%, 1.5%, 1.25% and 1% of plant capacity at 0, 25, 50 and 75 s respectively in area-2 of interconnected thermal system with area-1 remain undisturbed. The response of frequency and inter-area tie line power variations are represented in Figure 8. It is inferred from the plots, the oscillations are ramped up for the sudden change in load and the controller deteriorates these oscillations and quickly moves to a new equilibrium state. For the consecutive changes in the load demand, the gain parameters of proposed controller are adaptively adjusted through Lyapunov notion of Hopfield network by minimizing the
energy function to the new equilibrium state from the previous state. The variation in gain values of controller is depicted in Figure 9. The result shows that the gain values of the controller are not static and it changes for occurrence of any uncertainties into the system due to dynamical behaviour of GHNN.

To test the feasibility of the controller, the change in load demand in area-2, solar and wind power variation in both areas of HPS are considered simultaneously as depicted in Figure 10. The result obtained for these consecutive changes is shown in Figure 11. It is seen that the response is settled to steady state with minimum overshoots/undershoots without any oscillation by the proposed controller than other controllers through its self-adaptiveness of gain parameters.

4.5 Case-2: Sensitivity analysis

The sensitivity analysis was carried out to test the robustness of tuned values of controller gains for its real time applicability. To analyse this, the parameters such as loading and inertia of the system are widely varied from their nominal operating conditions and its performance is compared. The system loading was perturbed by increase in 80% and decrease in 10% from its nominal loading respectively. These changes in system loading have adverse impact on time and gain constant of PS block in ALFC application. Thus, the change in frequency and tie-line power for these wide variations in system loading is presented in Figure 12. It is seen that the change in the response is less indicating optimal value of controller gains. Similarly, the inertia of the system is increased by 25% and decreased by 10% from its nominal value \((H = 5)\), which affects the time constant of the PS that results in infinitesimal changes in the frequency and tie-line power. Even these changes are controlled by the designed robust controller. The result obtained for these changes in inertia is portrayed in Figure 13.
4.6 Case-3: New England 39-bus system

In this case, a large realistic power system of New England 39-bus power system with 10 generators is employed to test the performance of the proposed control scheme. The 39-bus system comprises of 10 generators, 19 loads, 34 transmission lines and 12 transformers. The system is realized as 3-area interconnected system to study the LFC task and the parameters for simulation are given in [4, 6]. Area-1 has three generators (G1, G2 and G3) at bus 1, 2 and 3, Area-2 has three generators (G8, G9 and G10) at bus 8, 9 and 10, and Area-3 has 4 generators (G4, G5, G6 and G7) at bus 4, 5, 6 and 7. However, only 1 generator in each area is responsible for LFC task: G1 in Area-1, G9 in Area-2 and G4 in Area-3, respectively.

All the power generators in each area are employed with boiler dynamics, GRC and GDB. The total installed capacity of three-area is 881.2 MW with 218.96 MW of generation and 265.25 MW of load in Area-1, 232.83 MW of generation and load in Area-2, 180.05 MW of generation and 124.78 MW of load in Area-3. The area-1 and 3 are installed with wind power of 12 MW and STPG of 8 MW. An increase in load demand of 3.283, 0.233 and 3.601 MW is given area-1 to area-3, respectively. The dynamic response obtained for 39-bus test system is given Figure 14. It is observed that the proposed FOPID controller settles faster with minimum undershoots than other techniques presented although the non-linearities are considered in the simulation model. The results demonstrate the superior performance of proposed control technique and its robustness for large realistic power system.

4.7 Case-4: Comparative analysis with other optimization algorithms

This section presents the comparative analysis of proposed technique of tuning FOPID controller with other recent benchmark optimization algorithms available in the literature to demonstrate the superiority of the method. To study this, a HPS model considered in case II-A was run with a step load perturbation of 0.025 and 0.015 p.u in area-1 and 2, respectively. The FOPID controller of two-area HPS was tuned using proposed MFO GHNN, atom search optimization (ASO: $K_p = -0.5775, K_i = -2.2125, \lambda = -0.8695, K_d = -3.6021, \mu = -0.7122$), Big Bang Big Crunch (BBBC: $K_p = 0.5616, K_i = -1.3375, \lambda = -0.8686, K_d = -2.5521, \mu = -0.9214$), Imperialist competitive algorithm (ICA: $K_p = -0.5398, K_i = -1.6303, \lambda = 0.8485, K_d = -0.9877, \mu = 0.7279$) and ant lion optimization (ALO: $K_p = -2.2081, K_i = 1.4142, \lambda = 0.8686, K_d = -1.6215, \mu = 0.8501$) method. The dynamic response obtained using different algorithms is given in Figure 15. The result reveals that the proposed method of tuning FOPID controller for ALFC application settles faster with minimum undershoots showing significant performance than other techniques presented. Further, the initial oscillations in the response were observed for all the optimization methods presented except the proposed approach of tuning the controller.

5 STABILITY ANALYSIS

Generally, for a linear time-invariant (LTI) system to be stable the roots of the characteristic polynomial should lie in the left half of complex plane. But, interestingly the fractional LTI system is stable even if the root lies in the right half of complex plane as defined by,

Matignon’s stability theorem [26, 24]: The fractional order transfer function $G(s) = C(s)/R(s)$ is stable if and only if, the
subsequent condition is satisfied in s-plane:

$$|\arg(\sigma)| > \frac{\pi}{2m}, \forall \sigma \in C, \quad R(\sigma) = 0 \quad (28)$$

where $\sigma = s^\alpha$, if $\sigma = 0$ is only single root of $R(s)$, then the system is unstable. The detailed steps for stability analysis are presented as follows:

The general characteristic polynomial of a fractional order controller is considered as

$$\alpha_0 s^{\beta_0} + \alpha_1 s^{\beta_1} + \cdots + \alpha_n s^{\beta_n} = 0 \quad (29)$$

It is assumed that $\beta_i = \frac{\nu_i}{m}$ and the above equation in $\sigma$-plane is defined as,

$$\sum_{i=0}^{n} \alpha_i s^{\nu_i} = \sum_{i=0}^{n} \alpha_i s^{m_i} = 0 \quad (30)$$

where $\sigma = s^{\frac{1}{m}}$ and $m$ is smallest common multiple of $\nu$.

For any given value of $\alpha_i$, the roots of (23) is $|\theta_\sigma| = |\arg(\sigma)|$ and the condition for stability is defined as

1. The system is stable if $\frac{\pi}{2m} < |\arg(\sigma)| < \frac{\pi}{m}$
2. The system is oscillatory stable if $|\arg(\sigma)| = \frac{\pi}{2m}$

Else the system is unstable.

To analyse the stability of the two-area system with FOPID controller, the above-mentioned stability notion is applied. As the HPS consisting of identical areas, stability analysis can be performed for the simple case of single-area reheat steam turbine system with non-linearities. For better understanding of stability analysis of proposed method, a single-area reheat steam turbine is considered. The closed loop transfer function of single-area system obtained from Figure 16 is expressed as [1],

$$\Delta F(s) = -\frac{G_D(s)}{1 + \left(\frac{1}{R}G_D(s)G_{GT}(s)\right)} \Delta P_D(s) \quad (31)$$

The above equation in terms of Laplace s-domain is written as follows,

$$\Delta F(s) = \frac{K_D}{1 + \frac{1}{R} \left(\frac{K_D}{R} + \frac{K_D}{GT} + \frac{K_D}{GT} \frac{1}{1 + \frac{1}{T_D} + \frac{1}{T_D} + \frac{1}{T_D}}\right)} \left(-\frac{\Delta P_D(s)}{s}\right) \quad (32)$$

The dynamic response $f(t)$ can be obtained by inverse Laplace Transform of (31) which involve the transfer function model of generator, turbine with reheat and PS that results in the transfer function of 4th order at the denominator. To reduce the mathematical complexity, the following assumptions were made as in [1]: a) practically, for a generator operating at constant speed the proportionality constant of generator and turbine is unity i.e. ($K_G = K_T = 1$). b) The time constant of generator and reheat turbine are assumed to be zero (i.e. $T_G = T_r = 0$). The simplified closed loop transfer function with following assumptions is given as,

$$\Delta F(s) = \frac{-K_D}{T_D} \frac{\Delta P_D(s)}{s^2 + \left(\frac{1 + \frac{K_D}{R}}{T_D}\right)} \quad (33)$$

Now, considering the FOPID controller transfer function (1) and rewriting the above equation with mathematical simplification results in,

$$\Delta F(s) = \frac{-K_D}{T_D} \frac{\Delta P_D(s)}{s^2 + \left(\frac{1 + \frac{K_D}{R}}{T_D}\right) + \left(\frac{K_D}{T_D} + K_D \frac{1}{s^\alpha} + K_D \frac{1}{s^\mu}\right)} \quad (34)$$
The characteristic equation representing the closed loop transfer function with FOPID controller is expressed as

\[ s^2 + \left(1 + \frac{K_p}{K_D s + \frac{K_D}{T_D}}\right) + j \left[1 - \lambda, \mu, s^0 \right] + j^{1-\lambda, \mu, s^0} K_D s^0 = 0 \]

(35)

In this case, the system is perturbed with an increase in load demand of 1% of plant capacity and the remaining parameters are as in the two-area system. It is claimed in this paper, the proposed FOPID controller is a self-adaptive PID controller and the gain values of controller are changing. For the purpose of analysis, the gain values of controller during load perturbation are taken once the frequency response settles down to steady state. The parameters of controller obtained from simulation are \(K_p = 0.00014, K_i = 0.01229, K_d = -2.786 \times 10^{-8}, \lambda = 0.67458, \mu = 0.001487\) and the 2nd order characteristic equation after mathematical analysis is,

\[ s^2 + 2.55084s + 0.07374s^3 = 0 \]

(36)

On rewriting above equation,

\[ s^{20} + 2.55084s^{10} + 0.07374s^3 = 0 \]

(37)

Transforming above equation in \(s\)-plane we get,

\[ s^{20} + 2.55084s^{10} + 0.07374s^3 = 0 \]

(38)

On solving the roots are,

\[ \sigma_{1,2} = 0.8731 \pm 0.2815i = |\arg(\sigma_{1,2})| = 0.311 \]

\[ \sigma_{3,4} = 0.5424 \pm 0.7369i = |\arg(\sigma_{3,4})| = 0.9363 \]

\[ \sigma_{5,6} = 0.0074 \pm 0.9109i = |\arg(\sigma_{5,6})| = 1.5627 \]

\[ \sigma_{7,8} = -0.5277 \pm 0.7370i = |\arg(\sigma_{7,8})| = 2.1922 \]

\[ \sigma_{9,10} = -0.8583 \pm 0.2815i = |\arg(\sigma_{9,10})| = 2.8247 \]

\[ \sigma_{11} = -0.0737 \pm 0.0000i = |\arg(\sigma_{11})| = 3.1416 \]

The remaining roots are \(\sigma_{12,13,...,20} = 0\). Among all the roots, the least value of argument of complex conjugate roots is

\[ \sigma_{1,2} = 0.8731 \pm 0.2815i = |\arg(\sigma_{1,2})| = 0.311 \]

considered for stability as detailed in [22, 26] and it satisfies the condition for stability \(\pi m < |\arg(\sigma)| < \frac{\pi}{m}\). Here, \(m = 10\) which implies the stability condition as \(-0.314 < 0.311 < 0.314\). Moreover, the condition \(|\arg(\sigma)| > \frac{\pi}{2}\) results in \(0.314 > 0.157\). It is observed that the argument of least complex roots satisfies the stability condition which result in stability of the system. Further it is found from the analysis, for the system considered the argument value of \(K = 1\) indicating the stable system and their corresponding pole position plot is shown in Figure 17. Since, \(q = 0.01\) the unstable region angle is 0.9 degree. It is inferred that the system has more stable area and their poles are found in stable region majorly though they lie on the right half of complex plane. Thus, stability of the system is analysed using Matignon’s stability theorem.

6 | EXPERIMENTAL VALIDATION USING RTDS

The proposed GHNN based FOPID controller is validated using Real-time digital simulator. It is an electromagnetic transient PS simulator that runs in HIL simulation with four outputs channel and developed by the OPAL-RT technologies. The experimental results for frequency oscillations are obtained for all aforementioned simulated cases. But, the dynamic frequency response of the system for uncertain changes in load demand in area-2, solar and wind power variation in both areas of HPS are recorded and presented in Figure 18. It is identified that the results obtained are promising as that of simulated results presented in Figure 11.

7 | CONCLUSION

This comprehensive work presents the combination of computational intelligence and GHNN technique for the design of FOPID controller for multi-area HPS considering the effect of GDB, GRC and boiler dynamics of thermal system and the presence of renewable sources. The results obtained show that the proposed FOPID controller outperforms compared to other controllers and the dynamics are rapidly damped out with
minimum steady state error. The results of the proffered controller significantly reduces the steady state error indices such as IAE, ITAE, ISE, ITSE and also improves the transient performance indices of settling time and peak overshoot. The work done by the controller is calculated in terms of control effort and the result reveals that the proposed fractional order controller performs with low control effort. Furthermore, the effectiveness of the controller is tested considering sudden change in solar power and wind power generation, system loading and inertia through sensitivity analysis. The results show that the gain values are adjusted automatically for these uncertainties in the system due to its self-adaptiveness of GHNN in Lyapunov sense. The stability of the system is examined by Matignon's theorem of stability. In addition, the simulation results obtained are validated by the HIL simulation run using digital simulator. The study of ALFC in presence of FACTS and HVDC devices using GHNN based controller design is the future scope of the work.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the TEQIP-III-COE—Alternate Energy Research (AER), Government College of Technology (GCT), Coimbatore, Tamil Nadu, funded by NPIU, TEQIP-III, New Delhi, India for providing facilities to carry out this research work.

REFERENCES

1. Elgerd, O.I.: Electric Energy Systems Theory – An Introduction, 2nd ed., Tata McGraw-Hill, New York (2007)
2. Peng, C., Zhang, J., Yan, H.: Adaptive event-triggering $H_{\infty}$ load frequency control for network-based power systems. IEEE Trans. Ind. Electron. 65(2), 1685–1694 (2007)
3. Arya, Y.: AGC performance enrichment of multi-source hydrothermal gas power systems using new optimized FOFPID controller and redox flow batteries. Energy 127, 704–715 (2017)
4. Lian, K., Xu, Y.: A robust load frequency control scheme for power systems based on second-order sliding mode and extended disturbance observer. IEEE Trans. Ind. Informat. 14(7), 3076–3086 (2018)
5. Mu, C., Tang, Y., He, H.: Improved Sliding mode design for load frequency control of power system integrated an adaptive learning strategy. IEEE Trans. Ind. Electron. 64(8), 6742–6751 (2017)
6. Bevrani, H., Dasshafar, F., Daneshmand, P.R.: Intelligent power system frequency regulation concerning the integration of wind power units. In: Wind Power Systems: Applications of Computational Intelligence, 1st ed., pp. 407–437. Springer Verlag, Heidelberg (2010)
7. Ma, M., et al.: Distributed model predictive load frequency control of the multi-area power system after deregulation. IEEE Trans. Ind. Electron. 64(6), 5129–5139 (2017)
8. Mohanty, B.: TLBO optimized sliding mode controller for multi-area multi-source nonlinear interconnected AGC system. Int. J. Electr. Power Energy Syst. 73, 872–881 (2015)
9. Elsisi, M., et al.: Bat inspired algorithm based optimal design of model predictive load frequency control. Int. J. Electr. Power Energy Syst. 83, 426–433 (2016)
10. Xu, D., et al.: A novel adaptive neural network constrained control for a multi-area interconnected power system with hybrid energy storage. IEEE Trans. Ind. Electron. 65(8), 6625–6634 (2018)
11. Ramachandran, R., et al.: Load frequency control of a dynamic interconnected power system using Generalised Hopfield neural network based self-adaptive PID controller. IET Gener. Transm. Distrib. 12(21), 5713–5722 (2018)
12. Naidu, K., et al.: Application of firefly algorithm with online wavelet filter in automatic generation control of an interconnected reheat thermal power system. Int. J. Electr. Power Energy Syst. 63, 401–413 (2014)
13. Yousefi, G.R., Haen Akbarzadeh, H., Hajjaj Khani Fini, M.: Comparative study on the performance of many-objective and single-objective optimisation algorithms in tuning load frequency controllers of multi-area power systems. IET Gener. Transm. Distrib. 10(12), 2915–2923 (2016)
14. Guha, D., Roy, P.K., Banerjee, S.: Study of differential search algorithm based automatic generation control of an interconnected thermal-thermal system with governor dead-band. Appl. Soft Comput. J. 52, 160–175 (2017)
15. Barisal, A.K., Lal, D.K.: Application of moth flame optimization algorithm for AGC of multi-area interconnected power systems. Int. J. Energy Optim. Eng. 7(1), 22–49 (2017)
16. Ghesarnejad, M.: An effective hybrid harmony search and cuckoo optimization algorithm based fuzzy PID controller for load frequency control. Appl. Soft Comput. J. 65, 121–138 (2018)
17. Morsali, J., Zare, K., Tarafdar Hagh, M.: Comparative performance evaluation of fractional order controllers in LFC of two-area diverse-unit power system with considering GDB and GRC effects. J. Electr. Syst. Inf. Technol. 5(3), 708–722 (2018)
18. Kesarkar, A.A., Selvaganesan, N.: Tuning of optimal fractional-order PID controller using an artificial bee colony algorithm. Syst. Sci. Control Eng. 3(1), 99–105 (2015)
19. Pan, I., Das, S.: Fractional order AGC for distributed energy resources using robust optimization. IEEE Trans. Smart Grid 7(5), 2175–2186 (2016)
20. Veerasamy, V., et al.: Load flow analysis using generalised Hopfield neural network. IET Gener. Transm. Distrib. 12(8), 1765–1773 (2017)
21. Wen, U.P., Lan, K.M., Shih, H.S.: A review of Hopfield neural networks for solving mathematical programming problems. Eur. J. Oper. Res. 198, 675–687 (2009)
22. Irudayaraj, A.X.R., et al.: A Matignon’s Theorem based stability analysis of hybrid power system for automatic load frequency control using atom search optimized FOPID controller. IEEE Access 8, 168751–168772 (2020)
23. Kler, D., Kumar, V., Rana, K.P.S.: Optimal integral minus proportional derivative controller design by evolutionary algorithm for thermal-renewable energy-hybrid power systems. IET Renewable Power Gener. 13(11), 2000–2012 (2019)
24. Choudhary, S.K.: Stability and performance analysis of fractional order control systems. WSEAS Trans. Syst. Control 9(1), 438–444 (2014)
25. Mirjalili, S.: Moth-flame optimization algorithm: A novel nature-inspired heuristic paradigm. Knowledge-Based Syst. 89, 228–249 (2015)
26. Matignon, D.: Stability properties for generalized fractional differential systems. ESAIM Proc. 5, 145–158 (1998)

How to cite this article: Ramachandran R, Satheesh Kumar J, Madasamy B, Veerasamy V. A hybrid MFO-GHNN tuned self-adaptive FOPID controller for ALFC of renewable energy integrated hybrid power system. IET Renewable Power Gener, 2021;15:1582–1595. https://doi.org/10.1049/rpg2.12134