A Matignon’s Theorem Based Stability Analysis of Hybrid Power System for Automatic Load Frequency Control Using Atom Search Optimized FOPID Controller

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ABSTRACT The large-scale penetration of intermittent Renewable Energy (RE) sources such as wind and solar power generation may cause a problem of frequency aberration of interconnected Hybrid Power System (HPS). This occurs when the load frequency control of interconnected system is unable to compensate the power balance between generation and load demand. Also owing to the enhancement of future transport, the Plug-in Electric Vehicle (PEV) plays a significant role to customer at demand side. Thus, the PEV can act as a power control to compensate the power balance in Renewable Energy integrated power system. This paper presents a physics inspired Atom Search Optimization (ASO) algorithm for tuning the parameters of Fractional Order Proportional-Integral-Derivative (FOPID) controller for Automatic Load Frequency control of HPS. In this proposed work, an attempt has been made to analyze the frequency stability of HPS using Matignon’s theorem. The interconnected HPS consists of reheat thermal power system, RE sources such as wind and solar thermal power generation associated with energy storage devices namely aqua electrolyzer, fuel cell and electric vehicle. The gain and fractional terms of the controller were obtained by minimizing the Integral Time Absolute Error of interconnected system. The robustness of ASO-tuned FOPID controller is tested on two-area HPS that was modelled using MATLAB/Simulink. The results obtained were then compared with other fractional order and classical integer order controllers. From the simulation results, it is inferred that the proposed ASO-tuned FOPID controller gives superior transient and steady-state response compared with other controllers. Moreover, the self-adaptiveness and robustness of the controller was validated to account for the change in RE power generations and system parameters. Furthermore, the effectiveness of the method is proved by comparing its performance with the recent literature works. The real-time applicability of proffered controller is validated in hardware-in-the-loop simulation using Real Time Digital Simulator.

INDEX TERMS Automatic load frequency control (ALFC), atom search optimization (ASO), fractional order proportional-integral-derivative (FOPID), hybrid power system (HPS), plug-in electric vehicle (PEV).

I. INTRODUCTION

In recent years, the size and complexity of electric power network have been tremendously increased due to integration of large number of RE sources: solar, wind, fuel cell (FC) and aqua electrolyzer (AE) etc. into the grid to meet the power demand of the system. The uncertain variations in load demand and RE sources lead to aberration in the grid frequency and tie-line power [1]–[3]. To slacks this, the generation and load balance of interconnected system is maintained
through Automatic Generation Control (AGC) or ALFC for secure and reliable operation of system. This is achieved through proper design of controller to govern the generation unit of power system. As a result, the change in frequency is retained within the nominal value of 0.1 Hz of system frequency [4], [5].

The conventional classical controllers such as Integral (I), Proportional Integral (PI), Proportional Integral Derivative (PID) and Integral minus Proportional Derivative (IPD) have been widely used by the power utilities to control the Area Control Error (ACE) of frequency and tie-line power deviation of interconnected system. In [6], PID controller gains were obtained using Ziegler and Nichols (Z-N) method, which resulted in effective operation. Conversely, the dynamics associated with the load and generation of the system makes this approach ineffective for system involving large uncertainties. To overcome this, the fuzzy and Artificial Intelligence (AI) based techniques were used to tune the gain parameters of controller for ALFC application. Although the design of fuzzy logic (FL) and Neural Network (NN) based classical controllers have self-adaptive properties to handle non-linearities in dynamical systems, their performance degrades if the network is not properly designed [7]–[9]. Numerous factors such as membership function, fuzzy rules, transfer function model, number of input and output layers and method of training the network can affect the output of the designed controller. Additionally, implementation of such controller in real-time for ALFC application is a cumbersome process and requires field expertise [8], [10]. Therefore, the gain parameters of classical controllers are obtained using population-based evolutionary computational intelligence approaches such as Genetic Algorithm (GA) [10], particle swarm optimization (PSO) [11], Quasi-Oppositional Harmony Search Algorithm (QOHA) [12], Grasshopper Optimization Algorithm (GOA) [13], Harris Hawks Optimization (HHO) [14], Hybrid Bacterial Foraging Optimization (HBFO) [15], Hybrid Improved Firefly-Pattern Search Optimization (HIF-PS) [16], Bat Algorithm (BA) [17] and other numerous approaches for controlling the ACE of interconnected multi-area multi-source power system. The obtained gain values of the controller from the above-mentioned methods have improved the efficiency and robustness of the system. However, the increase in growth of power system, uncertain variation in RE sources and load demand require more efficient controller to handle the uncertainties and non-linearities of the system [18]. The conventional classical controllers fail to respond and their performance degrades if the uncertainties of the system increase exponentially. Thus, the existence of robust control strategy such as H2/H∞, model free control strategy, Sliding Mode Control (SMC) and other modified form of SMC [19]–[21] proposed for ALFC application to overcome these limitations. However, these robust techniques necessitate the system state matrix for efficient implementation of control law. This intensifies the computational burden and control effort, creating difficulty for the implementation of controller in large-scale interconnected system that is linked to various state variables. Hence, optimal control parameter setting is still a major challenge for power system engineers. Therefore, to improve the performance of classical integer order controllers and to increase the robustness under uncertainties, an alternative control concept of FOPID has been introduced by the researchers.

The emergence of fractional calculus has made the transition from Fractional Order (FO) controllers into fractional order (FO) controllers by employing fractional terms in integral and differential terms of PID controllers. Such controllers are applicable for wider region of operation that stabilize the plant under control and offers improvement in closed loop response with robustness [22]. This is due to high degree of freedom introduced by additional tuning parameters of differential-integral operators [22], [23]. The use of FOPID controller in ALFC application also improves the system response by minimizing the frequency and tie-line error better than the IOPID controller does. The FOPID controller has two extra knobs corresponding to the integral and differential terms of IOPID controllers. This increases the flexibility for better design of control system and handles the system dynamics and non-linearities with robustness [24]. The FOPID controller has been observed expedient in various ALFC systems in conjunction with intelligence based heuristic methods such as Ant Lion Optimization (ALO) based fuzzy FOPID [25], Big Bang Big Crunch Algorithm (BBBC) [26], PSO [27], Imperialist competitive algorithm (ICA) [28], Selfish Herd Optimization (SHO) [29]. On the other hand, the vehicle to grid (V2G) technology in EV improves the performance of the system. In [30], the system with HVDC link for two-area thermal system by incorporating EV using Differential Evolution Particle Swarm Optimization (DEPSO) was analysed and their results are compared to IOPID. Similarly, Fractional Order Tilt Integral-Derivative (FOTID) has been employed with Artificial Bee Colony (ABC) Optimization to tune parameters in [31]. Nevertheless, the aforementioned literature work fails to study the effect of PEVs with RE sources; such as wind power, solar thermal power, energy storage systems namely AE and FC considering system non-linearities such as Governor Dead Band (GDB) and Governor Rate Constraint (GRC). This motivates the researchers to study their impact in ALFC system with FOPID controller and compare its performance with IOPID controller.

On the flipside, numerous heuristic methods have been used to tune the parameters of controller for ALFC application. However, optimizing the gain values of controller is still a major challenge for researchers due to the growth of uncertainties in generation and power system load. Due to these reasons, researchers widely trying to develop new AI methods for optimizing the gain values of controller to improve performance of the system. In this perspective, the proposed work considers a meta-heuristic physics inspired molecular dynamics-based optimization method called ASO to be used in the optimization of gain values of FOPID controller.
for ALFC application. The effectiveness of ASO has been proven for various real-time engineering applications such as parameter estimation of hydrogeologic problem [32], Polymer Exchange Membrane (PEM) fuel cell [33], et cetera. The result obtained demonstrates that ASO showed superior performance than Bacterial Foraging Optimization (BFO), GA and PSO algorithms due to its exploitation and exploration ability of reaching global minima [32]. In view of these observations, the proposed work uses ASO to tune the gain values and fractional order terms of FOPID controller for ALFC of multi-area system. Furthermore, the performance of fractional order controller is compared with various IO controllers. To study this, the parameters of the controller are tuned by minimizing the integral time absolute error (ITAE) of ACE as objective function. The ITAE is considered as the cost function to reduce overshoots and oscillations of system response, where it offers quicker settling time than any other performance criterion [34], [35]. Nonetheless, the analysis of frequency stability of HPS is limited in the literature. In [36], [37] the authors presented an eigen value analysis and model order reduction based bode analysis to analyze the frequency stability of the system. However, these approaches are inapplicable for analyzing the stability of fractional order systems. This motivates the author to attempt a new technique for frequency stability analysis. Thus, this work proposes a Matignon’s theorem-based stability analysis of fractional order controlled HPS. Astonishingly no literature works analyze the stability of fractional order controllers for HPS. In view of this, the prime contributions of this research are as follows:

(a) To derive the transfer model of HPS using Signal Flow Graph (SFG) approach and analyze its stability through Matignon’s theorem;

(b) To optimize the gain values of IO and FO controllers for HPS model considered using ASO algorithm and test the robustness of best optimal controller for stochastic variation in RE power generation and load demand; and

(c) The result (response of frequency and tie-line power variation) reveals that the performance of FOPID controller is impressively enhanced in terms of settling time, as well as peak overshoots and undershoots by an amount of 8% to 73 %, 5% to 87%, and 1% to 79%, respectively than those of FO and IO controllers for all cases. In addition, the steady-state error indices, such as Integral Absolute Error (IAE), ITAE, Integral Square Error (ISE) and Integral Time Square Error (ITSE) are also significantly improved.

The remainder of this paper is structured as follows: Section II describes the model of HPS with interconnected PEV. Section III portrays the analysis of transfer function model of HPS and Matignon’s stability theorem. Section IV elucidate the control scheme and its optimization using ASO algorithm. Section V portrays ASO optimization method for tuning FOPID controller. The results and discussion of system model under normal loading and uncertain change in generation and load demand with the stability analysis of HPS is presented in section VI. Hardware validation using Real Time Digital Simulator (RTDS) is presented in Section VII. Subsequently, the outcomes of this research are provided in Conclusion Section.

II. POWER SYSTEM MODEL

The multi-area HPS model shown in Figure 1 consists of reheat thermal system with associated system nonlinearities such as GDB and GRC, RE sources such as Wind Turbine Power Generation (WTPG), Solar Thermal Power Generation (STPG), AE, FC and PEV. The detail explanation of thermal power generation and its parameter for simulation is presented in [7], [38]. Further, the various RE model are described in detail [39] as follows:

A. WIND TURBINE POWER GENERATION MODEL

Wind energy is the fastest growing and extensively used RE source of power generation compared with other sources. The integration of WTPG into the grid may cause the grid frequency to fluctuate due to intermittent nature of wind power generation with fluctuating wind speed [40], [41]. In literature, numerous works on control of wind turbine has been proposed to resolve the frequency fluctuation problem [42]. Additionally, the pitch angle control strategy was suggested for smoothing the wind power generation. Moreover, energy storage devices such as AE and FC have been used to maintain the wind power balance during high and low speed wind to balance the frequency of grid. In this study, the system is linearized by a first-order lag transfer function with few approximations for analysis of WTPG penetration in HPS. This is represented in [37]:

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

(1)

where \(K_{WTPG}\) and \(T_{WTPG}\) represent the gain and time constant of WTPG, respectively.

B. SOLAR THERMAL POWER GENERATION MODEL

Solar energy is another major clean, carbon-free alternative source of power generation in power system using photovoltaic (PV) cells and concentrated solar power (CSP). In this work, the STPG is considered, where it consists of CSP collector that directs the solar irradiance into pipe carrying the working fluid such as oil or water. Then, this working fluid is moved into heat-exchanger for generation of steam to generate power using steam turbine. The non-linearity interlocked with the working component of solar collector and steam turbine of STPG system is linearized and represented in simplified form of transfer function in [10]:

\[
G_s(s) = \frac{K_s}{1 + sT_s} = \frac{\Delta P_{\text{STPG}}}{\Delta P_{\text{solar}}} 
\]

(2)

where \(K_T\) and \(K_s\) are the gain constant, \(T_T\) and \(T_s\) represent the time constant of steam turbine and solar collector, respectively.
C. AQUA ELECTROLYZER AND FUEL CELL MODELS
Energy storage devices such as AE and FC are incorporated into the system to enhance the power quality by stabilizing the frequency of HPS through power balance. The excessive power was generated from RE sources namely WTPG and STPG during high wind and irradiance conditions. Then, this power was directed to AE to generate hydrogen by decomposing water molecules ($H_2O$) into hydrogen ($H_2$) and oxygen ($O_2$). The generated hydrogen is stored in hydrogen storage tank through pipeline for maintaining the power bal-
D. PLUG IN ELECTRIC VEHICLE MODEL

Recently, PEV has been proposed for future transportation worldwide to reduce greenhouse gas emissions. This reduces the cost of charging and petroleum usage, while acting as a controllable load for power system that operates during night to stabilize the grid frequency [43]. Thus, the frequency oscillation can be overcome by the concept of charging and discharging between number of EVs connected to the grid. As such, a lumped PEV model is considered that charges up to 85% of SOC and controlled in the range of 85 ± 5% of State Of Charge (SOC) [44]. The PEV is assumed to participate in ALFC to regulate the frequency of interconnected system only if the state of charge (SOC) reaches 80% and act in controllable state with the maximum limit of 90% [45].

The detailed model of lumped PEV is portrayed in Figure 3 and parameters for simulation are given in [45]. The energy storage model of PEV is presented in Figure 4 with the stored energy provided to the grid is given by [45]:

$$E_{\text{control}}(t) = E_{\text{initial}}(t) + E_{\text{control-in}}(t) - E_{\text{plug-out}}(t) - E_{\text{LFC}}(t)$$

where $E_{\text{initial}}(t), E_{\text{control-in}}(t)$ and $E_{\text{plug-out}}(t)$ is the initial energy, increase in energy and decrease in energy due to plug-out, respectively. The energy signal $E_{\text{LFC}}(t)$ corresponding to LFC signal is obtained by integrating local central power $P_{\text{LFC}}$ according to [45]:

$$E_{\text{LFC}}(t) = \int_0^t P_{\text{LFC}}(t) \, dt$$

III. ANALYSIS OF HPS

To analyze the stability of HPS with proposed FO controller, a two-area interconnected HPS was considered. To achieve
this, initially the transfer function or state space model was initially required for analyzing the system stability. In view of this, the following section presents the analysis of HPS model and stability theorem.

A. TRANSFER FUNCTION MODEL OF HPS

The two-area interconnected HPS model portrayed in Figure 1 was considered for deriving the transfer function model of the system to study its stability. In the analysis, nonlinearities associated with the system are linearized, in addition the PEV components are eliminated to reduce the mathematical complexity of the system. The HPS model is represented in the form of SFG as given in Figure 5 to derive the closed loop transfer function of the system using Mason’s gain formula. To obtain the transfer function from the SFG, the input signal $P_{\text{Solar}}, P_{\text{Wind}}, \Delta P_{D1}$ and $\Delta P_{D2}$ as $I_1, I_2, D_1$ and $D_2$, respectively and the output signals were $\Delta f_1, \Delta f_2$ and $\Delta \phi_{\text{tie}}$. Figure 5 infers that the system involves 12 state vectors relating to overall transfer function of HPS.

\[
\begin{bmatrix}
\Delta f_1 \\
\Delta f_2 \\
\Delta \phi_{\text{tie}}
\end{bmatrix} =
\begin{bmatrix}
G_{11} & G_{12} & G_{13} & G_{14} \\
G_{21} & G_{22} & G_{23} & G_{24} \\
G_{31} & G_{32} & G_{33} & G_{34}
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2 \\
D_1 \\
D_2
\end{bmatrix}
\]

(8)

The Mason’s gain formula is given as,

\[
T = \sum_{k=1}^{k} P_k \Delta_k / \Delta
\]

(9)

where $P_k$ = Forward path gain of kth path. $\Delta_k = \text{obtained from the value of } \Delta \text{ by removing the loops that cross the } k^{th} \text{ forward path. } \Delta = 1 - \text{[sum of all individual loop gain]} + \text{[sum of loop gain product of all possible two non-touching loops]} - \text{[....]}$

where,

\[
A_1 = \frac{0.8 - \frac{0.2}{\pi} s}{1 + sT_{G1}}, \quad C_1 = \frac{0.8 - \frac{0.2}{\pi} s}{1 + sT_{G2}}
\]

$A_2 = $ closed loop transfer function of Reheat steam turbine with GRC.

\[
A_2 = \left[ \frac{1 + sK_1 T_{rl}}{1 + sT_{rl}} + \frac{U}{T_{rl}} \frac{U}{\gamma} \right]
\]

$C_2 = $ closed loop transfer function of Reheat steam turbine with GRC.

\[
C_2 = \left[ \frac{1 + sK_{G2} T_{r2}}{1 + sT_{r2}} + \frac{P}{G_{WTPG}} \frac{T}{s} \right]
\]

$A_3 = \frac{K_p s}{1 + sT_{ps1}}, \quad C_3 = \frac{K_p s}{1 + sT_{ps2}}, \quad G_c = K_p + \frac{K_i}{s} + K_d s^\mu$

$A_4 = -\frac{1}{R_1}, \quad C_4 = -\frac{1}{R_2}, \quad A_5 = B_1, \quad C_5 = B_2, \quad C_6 = \frac{2\pi T_{12}}{s}$

$R_1 = 2G_1G_2 = 2 \times \left( \frac{K_S}{1 + sT_S} \right) \times \left( \frac{K_T}{1 + sT_T} \right)$

$R_2 = 3G_3 = 3 \left( \frac{K_{WTPG}}{1 + sT_{WTPG}} \right)$

$R_3 = G_4 + 2G_5 G_6 G_7 = K_H + 2 (1 - K_H)$

To determine $\Delta$, the sum of all individual loop gain and the sum of loop gain product of all possible two non-touching loops are to be calculated. From Figure 5, it is evident that there are 8 individual loops as given below:

$P_{11} = -A_1A_2A_3A_4, \quad P_{21} = G_c A_1 A_2 A_3 A_5,$

$P_{31} = -A_3 C_6, \quad P_{41} = G_c A_1 A_2 A_3 C_6$

$P_{51} = -C_1 C_2 C_3 C_4, \quad P_{61} = G_c C_1 C_2 C_3 C_5$

$P_{71} = C_3 C_6 A_{12}, \quad P_{81} = -G_c C_1 C_2 C_3 C_6 A_{12}$

Also, there are 12 combinations of loop gain product of all possible two non-touching loops as stated below:

$P_N1 = P_{11} P_{51}, \quad P_N2 = P_{11} P_{61},$

$P_N3 = P_{11} P_{71}, \quad P_N4 = P_{11} P_{81}$

$P_N5 = P_{21} P_{51}, \quad P_N6 = P_{21} P_{61},$

$P_N7 = P_{21} P_{71}, \quad P_N8 = P_{21} P_{81}$

$P_N9 = P_{31} P_{51}, \quad P_N10 = P_{31} P_{61},$

$P_N11 = P_{41} P_{51}, \quad P_N12 = P_{41} P_{61}$
\[ \Delta = 1 - \text{[sum of all individual loop gain] + [sum of loop gain product of all possible two non-touching loops]} \]

\[ \Delta = 1 - \left[ P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 \right] \\
+ \left[ P_{N1} + P_{N2} + P_{N3} + P_{N4} + P_{N5} + P_{N6} + P_{N7} + \right] \\
+ \left[ P_{N8} + P_{N9} + P_{N10} + P_{N11} + P_{N12} \right] \]

(10)

By simplifying the above equation, we get,

\[ \Delta = \left[ (-A_1 A_2 A_3 A_4 + G_c A_1 A_2 A_3 A_5 - 1) \right] \\
\times \left[ -C_1 C_2 C_3 C_4 + G_c C_1 C_2 C_3 C_5 \right] \\
+ \left[ -C_3 C_6 + G_c A_1 A_2 A_3 C_6 \right] \\
\times \left[ -C_1 C_2 C_3 C_4 + G_c C_1 C_2 C_3 C_5 - 1 \right] \]

(11)

To determine the transfer function from \( I_1 \) to \( \Delta f_1 \):

\[ \frac{\Delta f_1}{I_1} = G_{11} = \frac{P_1 \Delta_1 + P_2 \Delta_2 + P_3 \Delta_3}{\Delta} \]

(12)

where

\[ P_1 = R_1 R_3 A_3, ~ P_2 = R_1 R_3 C_6 A_3 \]
\[ P_3 = -R_1 R_3 C_3 C_6 G_c A_1 A_2 A_3 \]
\[ \Delta_1 = 1 - (P_{51} + P_{61} + P_{71} + P_{81}), \Delta_2 = \Delta_3 = 1 \]

Substituting the values in (12) we get,

\[ G_{11} = \frac{(R_1 R_3 A_3) \left[ 1 + C_1 C_2 C_3 C_4 - G_c C_1 C_2 C_3 C_5 - C_3 C_6 a_{12} \right]}{\Delta} \]

\[ + R_1 R_3 C_3 C_6 A_3 - R_1 R_3 C_3 C_6 G_c A_1 A_2 A_3 \]

(13)

Similarly, the transfer function of \( \Delta f_1 \) with respect to \( I_2, D_1 \) and \( D_2 \) are as follows,

\[ \frac{\Delta f_1}{I_2} = G_{12} = \frac{(R_2 R_3 A_3) \left[ 1 + C_1 C_2 C_3 C_4 - G_c C_1 C_2 C_3 C_5 - C_3 C_6 a_{12} \right]}{\Delta} \]

\[ + R_2 R_3 C_3 C_6 A_3 - R_2 R_3 C_3 C_6 G_c A_1 A_2 A_3 \]

(14)

\[ \frac{\Delta f_1}{D_1} = G_{13} = \frac{(-A_3) \left[ 1 + C_1 C_2 C_3 C_4 - G_c C_1 C_2 C_3 C_5 - C_3 C_6 a_{12} \right]}{\Delta} \]

(15)

\[ \frac{\Delta f_1}{D_2} = G_{14} = \frac{-C_3 C_6 A_3 + C_3 C_6 G_c A_1 A_2 A_3}{\Delta} \]

(16)

As like \( \Delta f_1 \), the transfer function model for \( \Delta f_2 \) and \( \Delta \text{p} \text{tie} \) with respect to \( I_1, I_2, D_1 \) and \( D_2 \),

\[ \frac{\Delta f_2}{I_1} = G_{21} \]
\[ \frac{\Delta f_2}{I_2} = G_{22} \]
\[ \frac{\Delta f_2}{D_1} = G_{23} \]
\[ \frac{\Delta f_2}{D_2} = G_{24} \]
\[ \frac{\Delta \text{p} \text{tie}}{I_1} = G_{31} \]
\[ \frac{\Delta \text{p} \text{tie}}{I_2} = G_{32} \]
\[ \frac{\Delta \text{p} \text{tie}}{D_1} = G_{33} \]
\[ \frac{\Delta \text{p} \text{tie}}{D_2} = G_{34} \]

(17)

The transfer function accomplished from the above analysis for various inputs were used to analyze the stability of HPS.

**B. MATIGNON’S THEOREM BASED STABILITY ANALYSIS**

In general, for any Linear Time Invariant (LTI) system to be stable, the roots of the characteristic equation should lie in the left half of the s-plane. However, the fractional-order LTI system is stable even if the roots lie in the right half of the s-plane as defined by:
Matignon’s stability Theorem: The fractional order transfer function \( G(s) = \frac{Y(s)}{R(s)} \) is stable if, in s-plane, the following condition is met only if \([46], [47]\):

\[
|\arg(\sigma)| > \frac{\pi}{2}, \quad \forall \sigma_i \in \mathbb{C}, i^{th} \text{ root of } R(\sigma) = 0, \quad \text{where } \sigma = s^q
\]  

(25)

If \( s = 0 \) is the only single root of closed loop characteristic equation, then the system remains unstable. Thus, the stability region of fractional order system by Matignon’s stability theorem is also depicted in the form of Figure 6. The detailed steps for stability analysis are conferred as follows: Consider, the general fractional order transfer function characteristic equation for stability assessment of the system as:

\[
\alpha_0 s^\beta_0 + \alpha_1 s^\beta_1 + \ldots + \alpha_n s^\beta_n = 0 \quad (26)
\]

where

\[
\beta_i = \frac{\nu_i}{\nu}
\]

Let the fractional terms of the characteristic equation are mapped from s-plane to σ-plane, to make the system of equation linear integer order:

\[
\sum_{i=0}^{n} \alpha_i s^{\nu_i} = 0
\]

(27)

where \( m \) is the least common multiple of \( \nu \) and \( \sigma = s^k \). For every value of \( \alpha_i \), the roots of (27) is

\[
|\Phi_\sigma| = |\arg(\sigma)|.
\]

Thus, the stability conditions for fractional order systems are illustrated as

1) If \( \frac{\pi}{2m} < |\arg(\sigma)| < \frac{\pi}{m} \), the system is stable.
2) If \( |\arg(\sigma)| = \frac{\pi}{2m} \), the system is oscillatory stable.

If not, the system is unstable. The above statement of fractional order system of stability of notion is applied to multi-area HPS with fractional order controllers.

IV. CONTROL SCHEME

The performance of power system is highly reliable on design of controller and proper selection of objective function to design the control parameters. In general, the conventional IO controllers are widely used for ALFC operation in most of the literature studies. However, the increase in number of tuning knobs or control parameters improves the system performance to the desired level. Hence, the FOPID controller has been used in this study. The generalized control block diagram representing Figure 1 is portrayed in Figure 7. The FOPID controller has achieved considerable attention in the last few years. The fractional order controller emerges from Fractional Order Calculus (FOC) and this study utilizes the CRONE approximation suggested by oustaloup for designing FOPID controller \([48]\). The application of FOPID controller has been proved efficient in various domains such as nuclear reactor \([49]\), robotics \([50]\), power electronics \([51]\) and process control \([52]\). The transfer function of FOPID controller in s domain can be defined as \([48]\),

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

(28)

where \( K_p, K_i \) and \( K_d \) are gain parameters of FOPID controller, \( \lambda \) and \( \mu \) are the fractional order terms lies in the range of \((0,1)\). In this work, each guess value of the differ-integral terms \( \lambda \) and \( \mu \) during optimization process is rationalized with the Oustaloup fifth order rational approximation within the chosen frequency range of \( \omega \in 10^{-2}, 10^2 \text{rad/s} \) \([27]\). To design the control parameters for effective performance of controller, one of the steady state performance criteria such as IAE, ITAE, ISE or ITSE has to be used. In this work, the objective function of ITAE was employed because it offers superior performance than other performance indices \([34]\).
This can be defined in terms of ACE as:

\[
J = \text{ITAE} = \int_0^1 [|e(t)|] \, \, . \, dt \quad (29)
\]

where,

\[
e(t) = K_p \text{ACE} + K_i \int_0^t \text{ACE} \, dt + K_d \frac{d\text{ACE}}{dt} \quad (30)
\]

Subjected to:

\[
\begin{align*}
K_p^\text{min} &< K_p^i < K_p^\text{max} \\
K_d^\text{min} &< K_d^i < K_d^\text{max} \\
\mu^\text{min} &< \mu^i < \mu^\text{max} \\
K_i^\text{min} &< K_i^i < K_i^\text{max} \\
\lambda^\text{min} &< \lambda^i < \lambda^\text{max}
\end{align*}
\] (31)

V. ATOM SEARCH OPTIMIZATION

ASO is an optimization algorithm inspired by molecular dynamics of an atom based on atomic theory. In microscopic perspective, a matter is composed of indivisible number of atoms bounded by covalent bonds that vary in size and structure. In general, any substances made up of atoms that possess mass and volume. All atoms in the matter interact through microscopic interaction in constant motion irrespective of its state, and results in complex structure. Thus, the interaction force between the atoms has two primary characteristics such as repulsive and attractive forces which are depicted in Figure 8. During their interaction, the repulsive force of an atom avoids the crowdedness and trapping of local minima by increasing the exploration ability of the search region. As the distance between the atom increases, the repulsive force decreases that intensify the attractive force of atom by exploiting the solution gradually to global minima. Thus, the ASO algorithm possesses the characteristics of exploration and exploitation behaviour to reach the optimal solution. In ASO according to the distance between the atoms in the search space, each atom may attract or repel other atoms. As a result, heavier atoms have slower acceleration which makes them exploit the local space intensively in local space.

![Atomic forces system](image)

On the flipside, lighter atoms have an extraordinary acceleration, which makes them capable of exploring new regions in the search space. The process repeats until the convergence of solution is reached and this can be mathematically expressed as follows:

**Step-1:** Initialize the gain values of the controller randomly and its positions are characterized as

\[
X_i = (x_{i1}^1, \ldots, x_{id}^i, \ldots, x_{in}^i)
\]

for \(i = 1, 2 \ldots N\) where, \(x_{id}^i\) is the \(d^{th}\) position of \(i^{th}\) atom in \(D\) dimension space.

**Step-2:** Initialize number of atoms, its position, acceleration, mass and velocity (v). For assumed parameters compute the fitness function (29) of each atom.

**Step-3:** The mass of atoms and the forces acting between each atom are defined as

\[
M_i(t) = e^{\int_{t_0}^{t} F_{i(i)} - F_{i(best)(t)}}
\]

\[
m_i(t) = \frac{M_i(t)}{\sum_{j=1}^{N} M_j(t)}
\]

where, \(m_i\) is the mass of the \(i^{th}\) atom at \(t^{th}\) iteration, \(F_i(t)\), \(F_{i(best)}(t)\) and \(F_{i(worst)}(t)\) are the function fitness value, its worst and best values of atoms at \(t^{th}\) iteration, respectively. The worst (\(F_{i(worst)}(t)\)) and best (\(F_{i(best)}(t)\)) fitness can be written as,

\[
F_{i(best)}(t) = \min_{j \in \{1, 2, \ldots, N\}} F_{i(j)}(t)
\]

\[
F_{i(worst)}(t) = \max_{j \in \{1, 2, \ldots, N\}} F_{i(j)}(t)
\]

**Step-4:** During the initial stage of iterations, to intensify the exploration ability of atom in the search space each atom should communicate through numerous atoms with better fitness values from its neighbours \(K\). To improve the exploitation characteristics at the end stage of iterations, the atom needs to interact with its \(K\) neighbours, which will result in fewer atoms, thus having better fitness value. As \(K\) gradually decreases with lapse of iterations corresponding to function of time, it can be reckoned as

\[
K = N - (N - 2) \times \sqrt{\frac{T}{T}}
\] (36)

**Step-5:** Compute the interaction force \(F_i\) and the constraint force \(G_i\) using (37), (38).

\[
F_i^j(t) = \sum_{j \in K_{best}} \text{rand}_j F_{ij}^d(t)
\] (37)

\[
G_i^d(t) = \lambda(t) \left( x_{best}^d(t) - x_i^d(t) \right)
\] (38)

where \(\text{rand}_j\) is a random number lies between 0 and 1. The Lagrangian multiplier \(\lambda\) is defined as

\[
\lambda(t) = \beta e^{\frac{-x}{\beta}}
\] (39)

where \(\beta\) is the multiplier weight, \(x_{best}^d(t)\) represents \(d^{th}\) position of the best atom obtained at \(t^{th}\) iteration, \(x_i^d(t)\) depicts
The $i^{th}$ position of the best atom obtained at $t^{th}$ iteration. **Step-6:** Update the acceleration, velocity and position of each atom using the following equations.

$$a_{id} (t) = \frac{F_{id} (t)}{m_{id} (t)} + \frac{G_{id} (t)}{m_{id} (t)} = -\alpha \left(1 - \frac{t - 1}{T}\right)^3 e^{-\frac{20t}{T}}$$

$$v_{id}^{d}(t + 1) = rand \cdot v_{id}^{d}(t) + a_{id}^{d}(t)$$

$$x_{id}^{d}(t + 1) = x_{id}^{d}(t) + v_{id}^{d}(t + 1)$$

where $\alpha$ is the depth weight and $T$ is the maximum number of iterations.

**Step-7:** When the change in fitness value is reaching the $x_{best}$, grab the optimized gain values of the controller. Otherwise repeat the Steps 2 to 7 until the terminating condition is reached.

Conclusively atoms with larger mass and best fitness values result in a lower acceleration, leading to local search of optimization. Atoms with lower fitness value have the lighter mass, indicating a global search of method. Hence, the location of the atom gives the best optimal solution by minimizing the ACE of interconnected HPS. The parameters initialized for the proposed method are: maximum iteration $= 100$, Atom Numbers $= 50$, $\beta = 0.2$, $\alpha = 50$. For better clarity, the detailed procedure for tuning controller gains is also depicted in Figure 9. The obtained tuned values of controller parameters using ASO algorithm is given in Table 1.

**VI. RESULTS AND DISCUSSIONS**

This section presents the time domain analysis of multi-area multi-source HPS with FO and IO controllers for ALFC application tuned using ASO algorithm. The system is designed using MATLAB/Simulink and the parameters used for modelling are given in Appendix. The dynamic behaviour of the interconnected HPS is tested for random variation in RE sources and load demand to prove the effectiveness and superiority of proposed FOPID controller. The detailed explanation on simulation results is discussed in forthcoming sub-sections.

**Case A:** In this study, the HPS model consists of reheat thermal power generation with GRC of 3% p.u. MW/min and GDB of 0.05%, RE sources such as wind and solar thermal power with energy storage devices of AE and FC connected into the system for power balance. The two-area system considered is an identical area, operating with the Step Load Change (SLP) of 0.025 p.u. and 0.015 p.u. of plant capacity in area 1 and area 2, respectively. The dynamic response of frequency deviation and tie-line power variation corresponding to these changes are recorded in Figure 10. The total power generation to meet the load demand ($\Delta P_D$) can be expressed as

$$P_s = P_{\text{Thermal}} + P_{\text{Wind}} + P_{\text{Solar}} - P_{\text{AE}} + P_{\text{FC}}$$

Figure 10 infers that the system dynamic responses of frequency and tie-line power oscillates for I, PI, Fractional Order Integral (FOI) and Fractional Order Proportional Integral (FOPI) controller without reaching its steady state. However, the steady state error has been reduced drastically to zero by the PID and FOPID controller tuned using ASO algorithm. The transient performance indices such as settling time, rise time, peak magnitude, peak time, peak-overshoot and peak-undershoot, and steady state performance indices of IAE, IATE, ISE and ISTE for all IO and FO controllers of HPS are represented in Tables 2 to 12. It is observed that the system responds quickly with minimum settling time, over and undershoots by the FOPID controller compared to PID and other controllers. Similarly, the steady state indices are

| Type of Controller | Gains | Case 1 | Case 2 |
|--------------------|-------|--------|--------|
| I                  | $K_i$ | -0.2065 | -0.1911 |
| PI                 | $K_p$ | -0.1649 | -0.1595 |
|                    | $K_i$ | -0.2333 | -0.2349 |
| PID                |       | -2.5728 | -3.8592 |
| FOI                | $K_i$ | -0.3893 | -0.3076 |
|                    | $\lambda$ | 0.8697 | -0.4927 |
| FOPI               | $K_p$ | -0.0403 | -2.1555 |
|                    | $K_i$ | -0.5687 | -4.9383 |
|                    | $\lambda$ | 0.9832 | 0.9146 |
| FOPID              | $\mu$ | -0.7122 | -0.8968 |
|                    | $K_i$ | -2.2125 | -4.3473 |
|                    | $\lambda$ | -0.8695 | 0.9614 |
FIGURE 9. ASO method of optimizing controller parameters.

FIGURE 10. Frequency deviation and tie line power variation in two-area HPS.

remarkably improved by the FOPID controller compared to other controllers.

Case B: This Case is similar to case A, but PEV is connected in both areas of identical power system. The PEV responded faster than the conventional turbine-generator set and was mostly used for damping the peak value of frequency fluctuations originated due to variation in RE power generation. Subsequently, the steady state error of the system can be eliminated by the turbine and governor control of thermal system. The step load perturbations in both areas of HPS connected with PEV are similar to Case A, whereby the net power generation to meet this load demand is expressed as:

\[ P_s = P_{Thermal} + P_{Wind} + P_{Solar} - P_{AE} + P_{FC} \pm P_{PEV} \quad (44) \]

The change in frequency (\( \Delta f_1, \Delta f_2 \)) and tie line power variation (\( \Delta P_{tie} \)) for interconnected HPS with PEV is shown in Figure 11. It is seen that the overshoots and undershoots of the system response for all IO and FO controllers had reduced when compared with Case A. This is achieved by maintaining the power balance through charging and discharging of PEV into the ALFC system considered. As such, it is deduced that the system response is significantly predominant for FOPID controller compared to other controllers. This inference has also been perceived from the transient and steady state performance indices given from Table 5
TABLE 2. Performance parameters of frequency deviation in area 1 for Case A.

| Case | Performance Parameters | $\Delta f_1$ |
|------|------------------------|--------------|
|      |                        | I  | FOI | PI  | FOPI | PID | FOPID |
| A    | Settling Time (s)      | 16.4217 | 16.011 | 16.3082 | 18.5016 | 6.3281 | 5.8039 |
|      | Rise Time (s)          | 1.38x10^{-5} | 0.0013 | 0.002 | 4.74x10^{-5} | 2.91x10^{-6} | 2.24x10^{-6} |
|      | Peak Magnitude         | 0.0867 | 0.0852 | 0.1031 | 0.0837 | 0.039 | 0.0384 |
|      | Peak Time (s)          | 1.0151 | 0.9717 | 1.2157 | 0.9283 | 0.3766 | 0.3461 |
|      | Peak Over/Undershoots | 0.0119 | 0.0204 | 0.0056 | 0.0427 | 0.0072 | 0.0053 |
|      |                       | 0.08671 | 0.0851 | 0.103 | 0.0837 | 0.0398 | 0.0394 |

TABLE 3. Performance parameters of frequency deviation in area 2 for Case A.

| Case | Performance Parameters | $\Delta f_2$ |
|------|------------------------|--------------|
|      |                        | I  | FOI | PI  | FOPI | PID | FOPID |
| A    | Settling Time (s)      | 15.2398 | 14.9354 | 16.3083 | 19.5907 | 7.123 | 6.1947 |
|      | Rise Time (s)          | 4.28x10^{-4} | 0.0022 | 0.002 | 8.93x10^{-5} | 4.65x10^{-6} | 3.87x10^{-6} |
|      | Peak Magnitude         | 0.0897 | 0.0858 | 0.1031 | 0.0826 | 0.0265 | 0.0233 |
|      | Peak Time (s)          | 1.4975 | 1.4395 | 1.2157 | 1.3816 | 0.5347 | 0.4071 |
|      | Peak Over/Undershoots | 0.0102 | 0.0177 | 0.0046 | 0.0301 | 0.0062 | 0.0049 |
|      |                       | 0.0897 | 0.0857 | 0.1031 | 0.0825 | 0.0271 | 0.0232 |

TABLE 4. Performance parameters of frequency deviation in area 1 for Case B.

| Case | Performance Parameters | $\Delta f_1$ |
|------|------------------------|--------------|
|      |                        | I  | FOI | PI  | FOPI | PID | FOPID |
| B    | Settling Time (s)      | 18.2703 | 13.2592 | 19.86 | 6.0468 | 6.1799 | 5.338 |
|      | Rise Time (s)          | 1.97x10^{-5} | 0.1505 | 5.18x10^{-5} | 4.32x10^{-5} | 3.66x10^{-4} | 1.64x10^{-5} |
|      | Peak Magnitude         | 0.0868 | 0.0764 | 0.0829 | 0.0297 | 0.0392 | 0.0301 |
|      | Peak Time (s)          | 0.9921 | 0.9065 | 0.933 | 0.3201 | 0.3534 | 0.3201 |
|      | Peak Over/Undershoots | 0.0105 | 0.0102 | 0.0103 | 0.0074 | 0.0068 | 0.0051 |
|      |                       | 0.0868 | 0.0764 | 0.0829 | 0.0397 | 0.0392 | 0.0301 |

To Table 13. The time-domain parameters of settling time, rise time and peak time were remarkably enhanced for the FOPID controller by optimally minimizing ITAE index. Furthermore, the steady state error indices were greatly reduced for the proposed controller compared with other IO and FO controllers.

Case C: Sensitivity Analysis of FOPID Controller

To test the robustness of ASO method, the tuned gain and fractional order values of FOPID controller for HPS are subjected to uncertain changes in system parameters. So, the HPS model without PEV in case A is considered for sensitivity analysis of proposed ASO tuned FOPID controller.
TABLE 5. Performance parameters of frequency deviation in area 2 for Case B.

| Case | Performance Parameters | $\Delta f_2$ |
|------|-------------------------|--------------|
|      |                         | $I$ | $FOI$ | $PI$ | $FOPI$ | $PID$ | $FOPID$ |
| B    | Settling Time (s)       | 17.1225 | 12.491 | 18.8638 | 8.6665 | 7.2958 | 6.0764 |
|      | Rise Time (s)           | 5.60 x 10^{-4} | 0.257 | 6.21 x 10^{-4} | 7.35 x 10^{-5} | 0.003 | 2.8 x 10^{-5} |
|      | $|\text{Peak Magnitude}|$ | 0.0899 | 0.0771 | 0.0829 | 0.0184 | 0.0234 | 0.0187 |
|      | Peak Time (s)           | 1.531 | 1.4332 | 1.4332 | 0.3534 | 0.3829 | 0.3534 |
|      | $|\text{Peak-Over/Undershoot}|$ | 0.0089 | 0.0095 | 0.00922 | 0.0038 | 0.0055 | 0.0026 |
|      | $|\text{Peak-Undershoot}|$ | 0.0899 | 0.077 | 0.083 | 0.0184 | 0.0234 | 0.0187 |

TABLE 6. Performance Indices of frequency deviation in area 1 for Case A.

| Case | Performance Indices | $\Delta f_1$ |
|------|---------------------|--------------|
|      |                     | $I$ | $FOI$ | $PI$ | $FOPI$ | $PID$ | $FOPID$ |
| A    | IAE                 | 0.2624 | 0.2415 | 0.2858 | 0.2688 | 0.0563 | 0.0515 |
|      | ITAE                | 1.007 | 1.144 | 1.084 | 1.405 | 0.3082 | 0.2515 |
|      | ISE                 | 0.013 | 0.0107 | 0.0175 | 0.0108 | 0.0009 | 0.0008 |
|      | ITSE                | 0.02158 | 0.01636 | 0.0272 | 0.0211 | 0.0007 | 0.0006 |

TABLE 7. Performance Indices of frequency deviation in area 2 for Case A.

| Case | Performance Indices | $\Delta f_2$ |
|------|---------------------|--------------|
|      |                     | $I$ | $FOI$ | $PI$ | $FOPI$ | $PID$ | $FOPID$ |
| A    | IAE                 | 0.2522 | 0.2197 | 0.2852 | 0.2629 | 0.0508 | 0.0478 |
|      | ITAE                | 0.9717 | 1.078 | 1.084 | 1.389 | 0.2945 | 0.2487 |
|      | ISE                 | 0.01258 | 0.0104 | 0.01752 | 0.0107 | 0.0007 | 0.0006 |
|      | ITSE                | 0.022 | 0.017 | 0.0272 | 0.0217 | 0.0006 | 0.0005 |

TABLE 8. Performance Indices of frequency deviation in area 1 for Case B.

| Case | Performance Indices | $\Delta f_1$ |
|------|---------------------|--------------|
|      |                     | $I$ | $FOI$ | $PI$ | $FOPI$ | $PID$ | $FOPID$ |
| B    | IAE                 | 0.2618 | 1.53 | 0.224 | 0.0249 | 0.0419 | 0.0246 |
|      | ITAE                | 1.011 | 0.9833 | 0.8566 | 0.05831 | 0.2714 | 0.0388 |
|      | ISE                 | 0.0132 | 0.0506 | 0.0103 | 0.0004 | 0.0006 | 0.0003 |
|      | ITSE                | 0.02183 | 0.9835 | 0.0155 | 0.00018 | 0.0004 | 0.0001 |

The system is subjected to change in system parameters such as SLP, inertia and loading of the system. To study this, the SLP of 1% in area-2 is considered with load demand of area-1 remain unperturbed to tune the FOPID controller of multi-area HPS. Then, the system has been perturbed with SLP of 3% and 5% and the new gain values for these
TABLE 9. Performance parameters of frequency deviation in area 2 for Case B.

| Case  | Performance Indices | $\Delta f_2$ |
|-------|---------------------|-------------|
|       | I       | FOI       | PI       | FOPI      | PID      | FOPID    |
| IAE   | 0.2522  | 1.519     | 0.2117   | 0.01735   | 0.0394   | 0.0169   |
| ITAE  | 0.9723  | 1.098     | 0.8105   | 0.0536    | 0.2849   | 0.0356   |
| ISE   | 0.01278 | 0.0497    | 0.0099   | 0.0002    | 0.0004   | 0.0001   |
| ITSE  | 0.0223  | 0.983     | 0.016    | 0.0392    | 0.0004   | 0.0001   |

TABLE 10. Performance parameters of tie line power deviation for Case A.

| Performance Parameters | Case-A |
|------------------------|--------|
|                        | I      | FOI     | PI      | FOPI      | PID      | FOPID    |
| $\Delta p_{tie}$       | 37.4831| 26.3849 | 34.268  | 26.4503   | 13.6546  | 7.6506   |
| Settling Time (s)      | 0.0308 | 0.0438  | 0.054   | 0.0106    | 0.00008  | 0.0025   |
| Rise Time (s)          | 0.0079 | 0.0078  | 9.10×10$^{-8}$ | 0.0076 | 0.0027   | 0.0027   |
| Peak Time (s)          | 1.2157 | 1.1655  | 2.7611  | 1.1655    | 0.6789   | 0.6392   |
| | Peak-Overshoot         | 0.0103 | 0.0076  | 0.0085  | 0.0076    | 0.0027   | 0.0024   |
| | Peak-Undershoot        | 0.0897 | 0.0006  | 0.0024  | 0.0019    | 0.00034  | 0.00001  |

TABLE 11. Performance parameters of tie line power deviation for Case B.

| Performance Parameters | Case-B |
|------------------------|--------|
|                        | I      | FOI     | PI      | FOPI      | PID      | FOPID    |
| $\Delta p_{tie}$       | 37.9965| 17.2087 | 36.5616 | 10.2466   | 9.5983   | 5.6503   |
| Settling Time (s)      | 0.0726 | 0.4652  | 0.0075  | 0.0071    | 0.0175   | 0.0047   |
| Rise Time (s)          | 0.0079 | 0.0069  | 0.0075  | 0.0021    | 0.0028   | 0.0022   |
| Peak Time (s)          | 1.2033 | 1.1391  | 1.1701  | 0.6512    | 0.6512   | 0.6319   |
| | Peak-Overshoot         | 0.0006 | 0.00049 | 0.00044 | 0.0002    | 0.00034  | 0.00018  |
| | Peak-Undershoot        | 0.0006 | 0.0004  | 0.000434| 0.0002    | 0.0003   | 0.00018  |

changes are obtained which is listed in Table 14. Subsequently, the dynamic performance of HPS for the optimum gain values obtained under above-mentioned change in SLP is compared with the parameters of $K_p$, $K_d$, $\mu$, $K_i$, $\lambda$ attained at 1% change in SLP condition as given in Figure 12. The results have shown that the dynamic response of the system has infinitesimal changes among the tuned values, thus claiming the robustness of the controller. Similarly, the inertia constant (H) and loading of the system is perturbed by ±50% and ±25% from nominal value of H=5 and 50% loading of plant capacity as shown in Figure 13 respectively. The parameters of the FOPID controller was retuned for the above specified changes and had its performance compared with the parameters of $K_p$, $K_d$, $\mu$, $K_i$ and $\lambda$ acquired under
nominal conditions. Figure 14 exhibits the system response for the gain values obtained under nominal conditions, which is robust for wide variation in system parameters and has good tolerance. Hence, the gain values obtained under nominal conditions is optimum and need not to be retuned for the occurrence of any uncertainties in system parameter.

A. SELF ADAPTIVENESS OF THE CONTROLLER

The self-adaptiveness of the controller is an essential property of controller for RE integrated HPS. The existence of intermittent nature of power generation from wind and solar thermal power generation needs to be studied. To assess this, random variation in the output of renewable energies and random load perturbation were applied to the HPS. Figure 15 illustrates the random wind power generation model, which consists of white noise block signal with low pass filter. Then, multiplied with the standard deviation to calculate the output fluctuation of wind power as [10],

$$\sigma_{wf} = 0.8\sqrt{P_{wf}}$$

Similarly, the solar thermal power system model is depicted in Figure 16 which consisted of random output power fluctuation from band limited white noise block with low pass filter.
The intermittent output power generated from this wind and solar thermal model is represented in Figure 17. The dynamic response for this random output power fluctuation of wind and solar thermal power are shown in Figures 18 and 19. It is clearly observed from the Figures 18 and 19 that the frequency and tie line power variations for the proposed FOPID controller had driven back the system quickly to a steady state compared with that by other classical controllers, even for the practically variable wind and solar thermal power. Additionally, the effect of change in random load demand was considered in Figure 20. The response of system frequency and tie line power fluctuation, as given in Figure 21 indicates that FOPID controller gives minimum overshoot/undershoot and settling time.
TABLE 13. Performance Indices of tie line power deviation for Case B.

| Performance Indices | Case-B       |
|---------------------|--------------|
|                     | I    | FOI  | PI    | FOPI  | PID   | FOPID |
| $\Delta P_{tie}$    |      |      |       |       |       |       |
| IAE                 | 0.0437 | 0.2382 | 0.0369 | 0.3333 | 0.0062 | 0.0027 |
| ITAE                | 0.3982 | 6.035  | 0.3158 | 0.01087 | 0.1003 | 0.0066 |
| ISE                 | 1.419x10^{-4} | 1.148x10^{-3} | 1.176x10^{-4} | 3.142x10^{-6} | 4.514x10^{-6} | 2.972x10^{-6} |
| ITSE                | 5.781x10^{-4} | 2.915x10^{-2} | 4.487x10^{-4} | 3.191x10^{-6} | 1.264x10^{-5} | 2.490x10^{-6} |

TABLE 14. Controller gain values for sensitivity analysis.

| Controller | Gains | 25% Loading | 75% Loading | H=7.5 | H=2.5 | 1% SLP in Area 1 | 3% SLP in Area 1 | 5% SLP in Area 1 |
|------------|-------|-------------|-------------|-------|-------|-----------------|-----------------|-----------------|
|            |       | 25% Loading | 75% Loading | H=7.5 | H=2.5 | 1% SLP in Area 1 | 3% SLP in Area 1 | 5% SLP in Area 1 |
| FOPID      | $K_p$ | -2.5877     | -1.0796     | -1.5554 | -0.2196 | -1.9532 | -0.9892 | -0.7275     |
|            | $K_d$ | -2.8262     | -5.9833     | -2.4845 | -2.334 | -4.7582 | -5.1112 | -2.004     |
|            | $\mu$ | 0.8993      | -0.7492     | 0.7504  | -0.8784 | -0.75   | -0.842  | 0.727     |
|            | $K_i$ | -4.8825     | -1.3472     | -6.2263 | -0.7119 | -3.0972 | -1.4997 | -3.4568    |
|            | $\lambda$ | 0.9225   | -0.9415     | 0.853  | -0.811 | -0.9265 | -0.8873 | 0.5892     |

FIGURE 20. Random Change in load demand.

FIGURE 21. Dynamic response of two area HPS for random load change.

B. STABILITY ANALYSIS OF HPS

For stability analysis, an identical two-area interconnected HPS with RE sources and energy storage devices was considered. As such, the system model considered for the proposed work is deemed identical. Therefore, it is enough to analyze the stability of one of the areas of multi-area HPS. In this context, the closed loop transfer function obtained for frequency response $\Delta f_1$ of area 1, using the analysis of HPS in section III can be expressed as:

$$\Delta f_1(s) = \frac{-1.4553s^{2.5817} - 0.37987s^{1.7122} + 0.020499s^{1.5817} - 2.3694s^{0.0053505s^{(0.7122)}} + 0.033373}{s^{(1.7122)} - 0.0090834s^{(0.7122)}}$$  \(45\)

The characteristic equation of (45) is,

$$s^{(1.7122)} - 0.0090834s^{(0.7122)} = 0$$  \(46\)

$$s^{171} - 0.0090834s^{71} = 0$$  \(47\)

The above equation is transformed from s-plane to $\sigma$-plane, resulting in:

$$\sigma^{171} - 0.00908 = 0$$  \(48\)

$$\sigma^{71}(\sigma^{100} - 0.00908) = 0$$  \(49\)

On solving the roots of the above equation, the outcome will be:

$$\sigma^{71} = 0, \quad \sigma^{100} = 0.00908$$  \(50\)

The above equation indicates the roots are real. Among the roots, 71 roots lie at the origin and remaining 100 roots are real value and identical roots of 0.00908. Now, the value
of roots 0.00908 is the minimal integer value and it lies between
\[-\frac{\pi}{100} \leq 0.00908 \leq \frac{\pi}{100} \Rightarrow -0.0314 \leq 0.00908 \leq 0.0314\]
This proves the HPS controlled by ASO tuned fractional order PID controller is stable by maintaining the system frequency and tie line power response within tolerable limits.

**VII. EXPERIMENTAL VALIDATION USING RTDS**

The proposed ASO based FOPID control scheme was validated using RTDS platform using digital simulator of OPAL-RT OP4510. The RTDS is capable of performing electromagnetic transient simulation and widely used by the researchers to validate the proposed method. This also provides an applicable platform to validate the overall performance of proposed controller for ALFC application of a two-area HPS against classical controllers. Figure 22 portrays the setup for testing the model of two area HPS. Figures 23 and 24 shows the result obtained for the frequency deviation in real time for Case A of the two-area HPS. It is observed that the settling time of the proposed ASO-FOPID control scheme exhibited minimum settling time without any fluctuation in system response. Thus, the simulation results obtained were deemed more promising for the proposed FOPID controller.

**A. COMPARISON OF DIFFERENT ALGORITHMS FOR HPS**

This section describes the effectiveness of physics inspired molecular dynamics based ASO algorithm by comparing its performance with recent meta-heuristic method of tuning FOPID controller. To analyze this, the FOPID controller parameter of studied HPS model is optimized using PSO, BBBC, ICA, HHO and ALO algorithms. The optimized gain and fractional order values of FOPID controller for various intelligence algorithms are as follows: ASO (K_p = -0.5775, K_d = -3.6021, µ = -0.7122, K_i = -2.2125, λ = -0.8695) PSO (K_p = -0.9998, K_d = -0.5173, µ = 0.8973, K_i = -0.9542, λ = 0.8733) BBBC (K_p = 0.5616, K_d = -1.8233, µ = -0.7401, K_i = -1.3375, λ = -0.5162) ICA (K_p = -0.5398, K_d = -1.9877, µ = -0.7279, K_i = -1.6303, λ = -0.8485) HHO (K_p = -0.5398, K_d = -1.9877, µ = -0.7279, K_i = -1.6303, λ = -0.8485) HHO (K_p = -2.2081, K_d = -1.6215, µ = -0.8501, K_i = -1.4142, λ = 0.8686) ALO (K_p = -1.3740, K_d = -2.5521, µ = -0.9214, K_i = -1.0577, λ = -0.7633). The dynamic response of frequency and tie-line power variation of various aforementioned optimized techniques is portrayed in Figure 25. The Result demonstrates that the proffered ASO method of tuning FOPID controller had led the system into responding to reaching a steady state by damping the oscillations quickly with minimum settling time and
overshoots/undershoots compared with that by other intelligence techniques presented. This inference has also been perceived in transient and steady state performance indices given in Tables 15 to 17.

VIII. CONCLUSION

The significance of AE-FC and PEV in ameliorating the performance of interconnected HPS to balance the system frequency is investigated for a two-area system. To study this, a maiden attempt has been made to tune the parameters of FOPID controller for ALFC application using physics inspired ASO algorithm. Initially, a hybrid system consisting of thermal with RE sources and energy storage is considered (Case A) followed by the integration of PEV into HPS (Case B). The significant conclusions arriving from the present work are as follows:

| TABLE 15. Performance parameters of frequency deviation in area 1 of different algorithms for HPS. |
|----------------------------------------------------|
| Performance Parameters                              |
| ≲f₁                                                         |
| ASO                                      | PSO       | BBBC     | ICA      | HHO      | ALO       |
|--------------------------------------------------------------------------|
| Settling Time (s)                     | 5.8039    | 11.6533  | 8.2305   | 8.6945   | 9.5920    | 6.4601    |
| Rise Time (s)                        | 2.24×10⁻⁶ | 0.0330   | 8.0001×10⁻⁴ | 3.274610⁻⁴ | 3.439810⁻⁴ | 0.0326    |
| | Peak Magnitude                  | 0.0384    | 0.0555   | 0.0568   | 0.0424   | 0.0404    | 0.0478    |
| | Peak Time (s)                   | 0.3461    | 0.6147   | 0.5779   | 0.4013   | 0.3619    | 0.4705    |
| | | Peak-Overshoots               | 0.0053    | 0.0000   | 0.0123   | 0.0066   | 0.0021    | 0.0048    |
| | | Peak-Undershoots             | -0.0394   | -0.0555  | -0.0568  | -0.0424  | -0.0404   | -0.0478   |

| TABLE 16. Performance parameters of frequency deviation in area 2 of different algorithms for HPS. |
|----------------------------------------------------|
| Performance Parameters                              |
| ≲f₂                                                         |
| ASO                                      | PSO       | BBBC     | ICA      | HHO      | ALO       |
|--------------------------------------------------------------------------|
| Settling Time (s)                     | 6.1947    | 10.7905  | 8.9937   | 8.9160   | 10.5190   | 6.5413    |
| Rise Time (s)                        | 3.87×10⁻⁶ | 0.0562   | 0.0014   | 5.567×10⁻⁴ | 5.8497×10⁻⁴ | 0.0556    |
| | Peak Magnitude                  | 0.0233    | 0.0698   | 0.0457   | 0.0290   | 0.0265    | 0.0634    |
| | Peak Time (s)                   | 0.4071    | 1.1508   | 0.9131   | 0.5413   | 0.4705    | 0.9887    |
| | | Peak-Overshoots               | 0.0049    | 0.0000   | 0.0123   | 0.0060   | 0.0016    | 0.0021    |
| | | Peak-Undershoots             | 0.0232    | -0.0698  | -0.0457  | -0.0290  | -0.0265   | -0.0634   |

| TABLE 17. Performance parameters of tie line power deviation of different algorithms for HPS. |
|----------------------------------------------------|
| Performance Parameters                              |
| ΔPtie                                                        |
| ASO                                      | PSO       | BBBC     | ICA      | HHO      | ALO       |
|--------------------------------------------------------------------------|
| Settling Time (s)                     | 7.6506    | 10.2301  | 13.772   | 16.5426  | 16.0619   | 9.9065    |
| Rise Time (s)                        | 0.0025    | 0.1555   | 0.0326   | 0.021    | 0.0217    | 0.1239    |
| | Peak Magnitude                  | 0.0027    | 0.0066   | 0.0047   | 0.0029   | 0.0027    | 0.0097    |
| | Peak Time (s)                   | 0.6392    | 1.8139   | 0.8764   | 0.6868   | 0.6511    | 1.6176    |
| | | Peak-Overshoots               | 0.0024    | 0.003    | 0.0047   | 0.0029   | 0.0027    | 0.0023    |
| | | Peak-Undershoots             | -0.00001  | -0.0066  | 2.6539×10⁻⁴ | 1.2101×10⁻⁴ | -47.854  | -0.0097   |
1) The performance of proposed ASO optimized FOPID controller is compared with other FO, FOPI, and IO controllers, namely, I, PI and PID controllers. The result exhibits significant improvement in transient performance indices, such as settling time, peak overshoots, undershoots, rise time, peak time and peak magnitude by an amount of 8% to 73%, 5% to 87%, 1% to 79%, 16% to 98%, 1.5% to 95% and 9.4% to 80% respectively for the proposed FOPID controller compared with other controllers. Furthermore, the measurement of steady state indices shows remarkable reduction in error indices, such as IAE, ITAE, ISE and ITSE respectively for the proposed FOPID controller compared with other controllers.

2) In addition, the robustness and self-adaptiveness properties of proposed ASO tuned FOPID controller was tested for the system with the following changes: change in SLP from 1% to 5%, change in inertia by ±50% from its nominal values, change in system loading by ±25% from base loading and random variation in renewable power generation such as wind and solar thermal power generation, and random change in load demand of the system. The dynamic response of the system under these changes is predominantly significant for the ASO tuned FOPID controller compared with other FO and IO controllers.

3) The stability of the system is also investigated using Matignon’s theorem of stability. Additionally, the effectiveness of the FOPID controller is exhibited by comparing with recent literature work of controller tuning methods. The result shows considerable amount of improvement by the project method of tuning FOPID controller than other techniques presented.

4) The simulation results obtained is validated using RTDS run in hardware-in-loop environment. Thus, the application of ASO for optimizing the gain parameters of controller provided fruitful results for the power system model studied. However, the study of effect of FACTS device in presence of RE power variation with automatic voltage regulation AVR is the future scope of the work.

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