Multi-verse optimizer based Fuzzy-PI controller for robust frequency regulation in thermal-hydro power system

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Abstract—This study presents a frequency regulation scheme using a fuzzy-based proportional-integral (FUZZY-PI) controller for two areas non-reheat thermal-hydro power system. Optimal tuning of controller parameters is achieved through a newly established metaheuristic algorithm called Multi-Verse Optimizer (MVO) algorithm. The superiority of the proposed controller has been proven by comparing it with recently published control approaches. The different figure of merits is used to evaluate the performance of the offered controller. The attained results confirm the effectiveness of the designed controller for studied power systems.

NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| i      | Subscript referring to area-i (i=1, 2) |
| P_{R_i} | area-i rated capacity in MW |
| P_{L_i} | Nominal loading of area-i (MW) |
| ΔP_{L_i} | Change in power demand of area-i (pu MW) |
| F      | Frequency (Hz) of the power system |
| β_i    | Frequency bias constant (pu MW/Hz) |
| T_{ij} | Synchronizing coefficient of tie line |
| R_i    | Regulation coefficient of speed governor (Hz/pu MW) |
| K_P    | Gain constant |
| T_P    | Time constant |
| a_{ij} | Participation factor between i^{th} and j^{th} areas |
| T_{G_i} | Speed governor time constant of thermal turbine (s) |
| T_{T_i} | Thermal turbine time constant (s) |
| T_D    | Speed governor transient droop time constant of hydro turbine (s) |
| T_R    | Speed governor reset time of hydro turbine (s) |
| T_H    | Speed governor time constant of hydro turbine (s) |
1. Introduction
Frequency regulation within the predefined limits is very important for sustaining the stable operation of the power system (PS) [1]. Four frequency control loops are present in power systems such as primary frequency control, secondary or supplementary control loop, tertiary frequency control loop, and emergency frequency control loop. Primary and secondary frequency loops are for generation side only, while tertiary and emergency control loops are for both generation and load side. If the frequency deviation is less than a specific value, the governor control (primary frequency control) is applied and sufficient to maintain the balance between generation and load demand. Though, if the frequency deviation increases some specific value then governor control is not sufficient, in that situation secondary control is necessary [2]. The secondary control or supplementary control is also stated as load frequency control (LFC). LFC is a secondary controller incorporated in the power system to curtail frequency oscillations and keep the tie-line power within the stated limit, in case of a sudden change in demand [3].

LFC is not a new area for research, as plenty of work can be found in the literature on LFC. Different types of control designs have been considered in previous researches such as structured H-infinity controller [4], decentralized LFC [5], applied ANFIS (adaptive neuro-fuzzy inference system) [6], [7], observer-based LFC [8]. Besides, applying evolutionary algorithms for the optimal tuning of controller parameters of different controllers (conventional and intelligent) is another widely used method for LFC lately by most of the researchers [9], [10], [11], [12].

A critical examination of the surveyed literature revealed, that a few researchers have combined fuzzy logic controller (FLC) with the conventional controller to compensate the limitations offered by conventional controllers. Furthermore, with the optimal tuning of scaling factors (input and output) with the help of evolutionary algorithms, improved performance of the fuzzy controller can be achieved. Therefore, the Multi-verse optimization algorithm (MVO) has been applied to attain optimal values of the tunable parameters of the proposed controller to achieve a better frequency response of investigated diverse power system. The main contribution and objectives of the proposed work are highlighted below:

- To project a novel Multi-verse optimization algorithm tuned Fuzzy-PI control strategy for the LFC mechanism for the proposed model.
- To verify the preeminence of the suggested controller by equating it with other lately published strategies in the literature [13]-[16] on the same platform.
- To examine the robustness of the proposed controller for different load variations.

2. Mathematical modeling of power systems under study
Power system investigated in this study is a two-area multi-source non-reheat thermal-hydro system [13]-[16] as represented in Figure 1. The detailed modeling of considered test systems has been available in respective references [13]-[16]. The detailed parameters of system components are provided in Appendix-A. The dynamics of different power units and their components included in considered test systems are as shown in Figure 1.

| Tw | Nominal starting time of water in penstock (s) |
|----|----------------------------------|
| ST | Settling time (in tolerance band of ±0.0005) |
| US | undershoot                        |
| OS | overshoot                         |
| FOMs | Figure of Merits |
3. Control Scheme

This section gives the brief overview of the fuzzy based PI controller and the algorithm used to optimize the controller parameters. The brief description of the proposed control scheme are as follows:

3.1 FUZZY based proportional–integral controller:

The fuzzy logic controller (FLC) is a human reasoning-based controller. This control technique is the best to use in control engineering problems when mathematical models are not present. The major limitation of FLC is designing of its membership functions (mfs) and its rule base. Because designing of mfs and rule base demands extreme expertise \[17\]. However, tuning of SFs/gains improves the system performance significantly which can be easily achieved nowadays with the help of evolutionary algorithms. Therefore, it is the utmost used way of optimizing the FLC. Consequently, by tuning of SFs, mfs, and standard rule-base can be engaged for different applications. The schematic of the controller structure showing the proposed control strategy is shown in Figure 2.

Figure 1. Transfer function model of two-area multi-source thermal-hydro PS

Figure 2. Schematic of proposed controller
Therefore, in this proposed study, MVO is implemented to get the optimal values of scaling factors \((K_1, K_2, K_p, \text{ and } K_I)\) by engaging the rule base and structure of mfs used Ref. [17]. Equation (1) denotes the mathematical relation between the input control signal and its corresponding power deliver by the proposed controller, whereas \(y\) is the output signal of the fuzzy block.

\[
\Delta P_c = -K_p y + \frac{K_i}{s} y
\]

(1)

The proposed constraints are as follows:

\[
K^{\text{Min}}_1 \leq K_1 \leq K^{\text{Max}}_1, \quad K^{\text{Min}}_2 \leq K_2 \leq K^{\text{Max}}_2, \\
K^{\text{Min}}_p \leq K_p \leq K^{\text{Max}}_p, \quad K^{\text{Min}}_i \leq K_i \leq K^{\text{Max}}_i
\]

3.2 The proposed cost function:

To achieve the best dynamic performance from the proposed fuzzy-PI controller, ITAE (integral of time-weighted absolute error) is selected as a cost function for minimization [18], [19]. Mathematical expression for ITAE is as given in (2):

\[
J_{\text{ITAE}} = \int_0^{t_{\text{sim}}} \left( |\Delta F_1| + |\Delta F_2| + |\Delta P_{\text{tie}}| \right) dt
\]

where \(t_{\text{sim}} (s)\) is the total simulation time.

3.3 Multi-Verse Optimizer (MVO) algorithm:

Mirjalili et al. have proposed a multi-verse optimization (MVO) in 2016 [20]. Authors used the multi-verse theory and three main phenomena namely black hole, white hole, and wormhole of the multi-verse theory are utilized for the design of MVO. In this algorithm, white and black holes participate in the exploration process and wormholes participate in the exploiting process. Considering some assumptions, a mathematical model of the multi-verse theory is formed based on the roulette wheel mechanism.

Let us suppose

\[
U = \begin{bmatrix}
    z_1^1 & z_1^2 & \ldots & z_1^d \\
    z_2^1 & z_2^2 & \ldots & z_2^d \\
    \vdots & \vdots & \ddots & \vdots \\
    z_n^1 & z_n^2 & \ldots & z_n^d
\end{bmatrix}
\]

(3)

\[
z_i^j = \begin{cases}
    z_i^j, & a_i < \text{NIR}(U_i) \\
    z_i^j, & a_i \geq \text{NIR}(U_i)
\end{cases}
\]

(4)

Where \(d\) and \(n\) indicate the number of variables and universes, respectively. \(z_i^j\) states the \(j^{\text{th}}\) parameter of the \(i^{\text{th}}\) universe, \(U_i\) specifies the \(i^{\text{th}}\) universe, \(\text{NIR}(U_i)\) is a standardized inflation rate of the \(i^{\text{th}}\)
In the universe, and $a_i$ is a random number between ranges 0 to 1. $z_k^j$ states the $j^\text{th}$ parameter of $k^\text{th}$ universe nominated by a roulette wheel selection mechanism.

Further, local search is accomplished by MVO algorithm with the following mathematically expression:

$$z_i^j = \begin{cases} z_j + \text{TDRC} \left( (\text{lb}_j + \text{ub}_j) a_4 + \text{lb}_j \right) & a_3 < 0.50 \\ z_j + \text{TDRC} \left( (\text{lb}_j + \text{ub}_j) a_4 + \text{lb}_j \right) & a_3 < 0.50 \\ z_i^j & a_2 \geq \text{WEP} \end{cases}$$

Where $j^\text{th}$ parameter of the best-universe created so far can be denoted by $z_j$, the lower bound and upper bound of the $j^\text{th}$ parameter can be specified by $\text{lb}_j$ and $\text{ub}_j$, respectively. $a_2$, $a_3$, and $a_4$ are random numbers in the range between 0 and 1[20]. Wormhole existence probability (WEPC) and traveling distance rate coefficients (TDRC) mathematically can be derived as follows:

$$\text{WEPC} = \min + 1 \left( \frac{-\min + \max}{L} \right)$$

$$\text{TDRC} = -\frac{q^{r/2}}{Q^{r/2}} + 1$$

Where, $Q$ and $q$ express maximum and current iterations, respectively. The accuracy of the exploitation over the iterations can be signified by $r$. The 0.2, 01, and 06 are the values of min, max, and $r$, respectively taken in this study [20].

### 4. Simulation Results

The MATLAB-SIMULINK environment (version R2013a) has been used to investigate the power system under examination as displayed in Figure 1. The values of SFs i.e. $K_1$, $K_2$, $K_p$, and $K_i$ of proposed controllers obtained by MVO are 1.8602, 1.1069, 1.6061, and 3.3119, respectively. The effectiveness of the proposed controller (MVO based FUZZY-PI) has been analyzed by comparing commonly used FOMs i.e. IAE, ITAE, ITSE, and ISE with recently published well-known controllers as available in the literature.

A sudden load change of 1.5% in area-1 at $t = 0$ s has been assumed to study the performance of the proposed controller in the investigated power system. The impact of this sudden load demand on frequency and tie-line power flow has been displayed in Figure 3, and obtained parameters are tabularized in Table 1. Profound observation reveals that the thermal-hydro system transient responses with the proposed controller are superior as compared to the previously proposed control strategies in terms of ST and all FOMs. Even though ICA: FPI controller shows the least value for US in area-1 and -2. However, the overall dynamic behavior of the studied test system with the suggested control methodology show satisfied response with least values in terms of ST ($\Delta F_{\text{ST Area-1}} = 0.78546$ s, $\Delta F_{\text{ST Area-2}} = 1.5395$ s, $\Delta P_{\text{tieST}} = 0.39165$ s). In addition, the proposed controller has attained least values of FOMs (IAE = 5.017 \times 10^{-3}, ITAE = 6.2178 \times 10^{-3}, ISE = 1.0069 \times 10^{-5}, and ITSE = 3.1372 \times 10^{-6}) compared to the other recently proposed well-known optimal controllers [13]-[16].
Figure 3. Frequency responses of both areas and tie line power deviation between the areas of PS.

Table 1. Numerical values of ST, US, OS and FOMs ($t_{sim} = 10$).

| Controllers       | $\Delta F_{ST\text{Area-1}}$ | $\Delta F_{US\text{Area-1}}$ | $\Delta F_{ST\text{Area-2}}$ | $\Delta F_{US\text{Area-2}}$ | $\Delta P_{\text{tieST}}$ | $\Delta P_{\text{tieUS}}$ | IAE | ITAE | ISE ($\times 10^{-5}$) | ITSE ($\times 10^{-5}$) |
|-------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------------|-----------------------------|-----|-----|-----------------------|------------------------|
| hFA-PS:PID [13]   | 3.0077                        | 0.01372                       | 4.448                        | 0.00672                       | 3.3009                      | 0.00231                     | 0.02535 | 0.03738 | 11.96                  | 8.5631                 |
| GWO:PID [14]      | 1.1552                        | 0.01523                       | 3.42                         | 0.00704                       | 2.5963                      | 0.00271                     | 0.02333 | 0.02558 | 15.107                 | 9.0909                 |
| BFOA:FPI [15]     | 1.3529                        | 0.00931                       | 2.81                         | 0.00289                       | 1.8907                      | 0.00108                     | 0.01185 | 0.01495 | 3.4819                 | 1.7575                 |
| ICA:FPI [16]      | 1.5297                        | 0.00640                       | 2.5284                       | 0.00161                       | 1.3883                      | 0.00061                     | 0.00766 | 0.01126 | 1.223                  | 0.69409                |
| MVO:FUZZY -PI     | 0.7854                        | 0.00688                       | 1.5395                       | 0.00181                       | 0.39165                     | 0.00056                     | 0.00501 | 0.00621 | 1.0069                 | 0.31372                |
5. Robustness Analysis

Robustness analysis has been carried-out in the studied power system to check the effectiveness of the proposed controller concerning unknown dynamics response subject to anonymous load disturbances. The system performance has been examined with different values of load change. The proposed controller is simulated with five distinct load perturbation combinations for area-1 and area-2 such as (a) \( \Delta P_{L1} = 0.15 \text{ p.u. MW} \), (b) \( \Delta P_{L2} = 0.15 \text{ p.u. MW} \), (c) \( \Delta P_{L1} = 0.15 \text{ p.u. MW} \) and \( \Delta P_{L2} = 0.20 \text{ p.u. MW} \) (d) \( \Delta P_{L1} = 0.25 \text{ p.u. MW} \) and \( \Delta P_{L2} = 0.05 \text{ p.u. MW} \), and (e) \( \Delta P_{L1} = 0.20 \text{ p.u. MW} \) and \( \Delta P_{L2} = 0.25 \text{ p.u. MW} \). The fluctuations in load demand have been assumed from 15% to 25% in area-1 and area-2 with random scenarios. The output responses of the studied power system in terms of both areas frequency and tie-line power flow between both areas concerning the assumed scenarios have been shown in Figure 4. The results demonstrate the stable operation of the designed controller in the presence of abrupt load demands during sudden instants. Hence, it can be determined that the MVO based Fuzzy-PI controller convey robust control and function properly during uncertain disturbances in the studied power system.

![Figure 4](image-url)
6. Conclusion
Critical analysis has been performed on two-area multi-source non-reheat thermal-hydro power system to confirm the efficacy of the proposed controller. Comparison has been done with recently published control approaches to validate the effectiveness of the proposed approach. The results reveal that the proposed MVO tuned Fuzzy-PI controller has more disturbance rejection capability and it rapidly achieves zero steady-state error as compared to ICA:FPI which is next to the best. Furthermore, robustness examination of the studied approach shows effective performance even in different loading conditions. Finally, the analysis affirms the applicability of the MVO-FPI controller to provide robust control for the thermal-hydro power system.

APPENDIX
Power system (hydro-thermal) Data [13]-[16]

\[ P_R=2000\text{MW}; \quad P_B=2000\text{MW}; \quad F_1=F_2=60\text{Hz}, \quad P_L=1000\text{MW}; \quad K_p=100 \text{ Hz/pu MW}; \quad T_p=20s; \quad T_{I1}=0.0707; \]
\[ \beta=0.4250 \text{ pu MW/Hz}; \quad a_{12}=-1.0; \quad R_2 = 2.40 \text{ Hz/pu MW}; \quad R_1=2.0 \text{ Hz/pu MW}; \quad T_{C1} = 0.08s; \quad T_T = 0.30s; \quad T_D =48.7s; \quad T_R = 5.0s; \quad T_H =0.5130s; \quad T_W =1.0s; \quad \Delta P_{L1} = 0.0150 \text{ pu MW}. \]

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