Nonlinear Load-Frequency Control: An Approach Using Optimized Hierarchical Fuzzy Systems

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***Abstract*— Load Frequency Control (LFC) has long been managed with PID controllers. However, nonlinear disturbance in power system caused PID controllers exhibiting a mediocre performance. As an alternative, Fuzzy Mamdani and Takagi Sugeno Kang Fuzzy (TSKF) controllers were predominantly deployed. However, the computational intractability due to torrential fuzzy rules limits further use of these techniques. As a result, an Optimal Hierarchical Takagi Sugeno Kang Fuzzy (OHTSKF) controller is proposed. In this model, TSFK breaks into several sub-systems and through hierarchical classification, extensive number of fuzzy rules is eliminated, reducing the executional time of solution. Further, the Cuckoo Optimization Algorithm (COA) is integrated into the model so as to improving the response quality subject to nonlinear load disturbance. Simulation results demonstrated that the proposed OHTSKF controller surpasses other Fuzzy Mamdani and TSFK and it can replace other techniques and be served as an efficient LFC system for utilities.**

Keywords-- Load Frequency Control, Fuzzy Controller, Takagi Sugeno Kang Fuzzy (TSK), Fuzzy Mamdani, Cuckoo Optimization Algorithm (COA), Non-linear System.

I. INTRODUCTION

Holding system frequency in a nominal range while load changes has long been one of the crucial tasks for system operators. Yet, this is of even greater concerns today, as the radical growth in size and complexity of present power systems has led to an undeniable complication [1-5].

To efficiently operate a power system, one must invariably ensure that the system frequency settled on a stable ground. In this sense, significant and uncontrollable change in frequency may lead to serious mal-operation of synchronous and induction motors in the system as their output characteristics varies with input frequency variations [6], [7].

A well-designed power system is generally represented by high power quality standards, nearly-fixed and stable frequency as well as wisely-regulated voltage [8-12]. As such, small breeze in active power (demand) will nonlinearly alter the frequency of the system while its voltage may be perturbed if the reactive power (VAR) absorption remains changing in the grid. To curb the frequency oscillations, Load Frequency Control (LFC) loop was developed, interlocking the power and frequency to the nominal values subject to time variation instances in operation. Given a number of interconnections among neighboring utilities, controlling load frequency required paying a great deal of attentions [13-17].

Various methods have been proposed to control load frequency. The use of classic controllers such as PID in industry yet remained prevail. Simplicity and under-nominal performance design for these controllers made them an available choice in the market [18], [19]. However, they pose serious challenges when subject to high frequency fluctuations, led in an inferior performance. It becomes a trouble especially when exposed to non-linear conditions such as Generation Rate Constraints (GRC), dead band of governor and abrupt change in system parameters [20-23].

Linear optimal control [24] technique proposed which offered easier control strategy but it found faint attention due to its impracticality, and lack of complete system information. More, the linearity characteristics of the controller itself may procure inaccurate and faulty control actions [25]. Reference [26] shows a hierarchical optimal robust controller implementation in power system LFC model. However, simulations ought to run for two hierarchical levels (one follows another consecutively) consist of system optimization and control system robustness verification levels.

In this paper, a LFC controller is developed by means of fuzzy controller. In this vein, fuzzy controller may obviate further demand for dynamic models [20-25]. Moreover it mathematically improves the control model via assigning a wider range for system deviations, considering non-linear elements such as governor's dead band, and importantly noticing that it avoids building transfer function for the model.

The use of Fuzzy controller in a classical and traditional forms were limited by two major drawbacks including 1) an excessive and explosive number of rules defined in the algorithm [27-30] and 2) a numerically unstable computational performance especially in LFC which inherently possesses a tremendous number of control parameters involved.

In this paper, the proposed hierarchical fuzzy control can both reduce the number of rules and complexity of control system. Further, the Cuckoo optimization algorithm (COA) was employed to further enhance the developed hierarchical fuzzy model in this work.

II. TIE–LINE CONTROL

In load frequency control systems with a primary control loop, power deviations in the first area (area 1) are caused by ramping up/down generation within area 1 and 2. It is however done by a change in transferring power at tie-line and a reduction in system frequency. Commonly several steps are taken to perform load frequency in a traditional fashion including a) retaining system frequency close to its nominal value B) governing undergoing power in tie-line within a predefined range C) controlling load variations between heterogeneous areas and within each homogenous area.

The ordinary load frequency system control based on tie – line bias control means a tendency in each area to reduce control error (ACE) as closely as zero. The control error signal in each area is a mix of frequency error and power deviation in tie-line which can be stated as:

$$ACE_i = \sum_{j=1}^{n} \Delta P_{ij} + K_i \Delta\omega_i \quad (1)$$

Area constant indicates the mutual amount remaining between neighboring areas as far as there existed an error. Proper control action can be made if the constant gears with the constant frequency of given area, that is, $B_i = \frac{1}{R_i} + D_i$. Hence, area control errors for a two-area system can be stated as:

$$ACE_1 = \sum_{j=1}^{n} \Delta P_{12} + B_1 \Delta\omega_1 \quad (2)$$

$$ACE_2 = \sum_{j=1}^{n} \Delta P_{21} + B_2 \Delta\omega_2 \quad (3)$$

ΔP_{12} and ΔP_{21} are the amount differences between scheduled power and current power flows in tie-line. Area error signals forms an appropriate power regulation in reference system. In a stable condition, ΔP_{12} becomes an infinitesimal amount, nearly zero. In this sense, the integral constant should be so small to prevent the area from galling into tracking mode.

III. TWO-AREA POWER SYSTEM

In most systems a number of generators are closely related to each other and each generator's deviation affects others. Besides, generator turbines have a tendency to draw similar responses. That is, these are called identical generators, creating multiple areas in systems. In most of the load-frequency simulation, two area non-linear turbine power systems with governor that possesses a saturation surface of [-0.2 to 0.2] is considered. Figure 1 shows simulated two-area system in MATLAB Simulink.

The state-space model in figure 2 is defined as follows:

$$X^{\cdot}(t) = Ax(t) + Bu(t) + Fd(t) \quad (4)$$

$$Y(t) = Cx(t) \quad (5)$$

$$X = [\Delta P_{C1} \Delta X_{G1} \Delta P_{T1} \Delta F_1 \Delta P_{tie} \Delta P_{C2} \Delta X_{G2} \Delta P_{T2} \Delta F_2]^T \quad (6)$$

$$U = [\Delta P_{C1} \Delta P_{C2}]^T \quad (7)$$

$$Y = [ACE_1 ACE_2]^T \quad (8)$$

$$ACE_i = \Delta P_{tiei} + B_i \Delta F_i \quad (9)$$

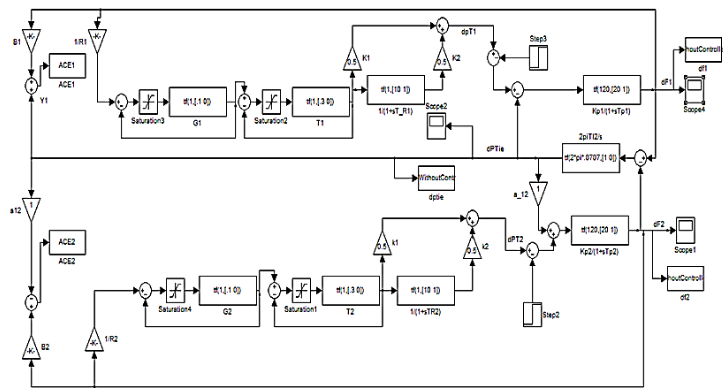

Figure 2. Two-area power system model

Where A, B, F, C are the matrices of the state, input, and output. Likewise, D(t), U(t), X(t) are the state vector and control of the turbulence that blows in.

IV. HIERARCHICAL FUZZY SYSTEMS

Designing a fuzzy system is subject to a number of rules in the system which may swell exponentially as the number of inputs in the system grows up. Let (*n*) inputs for a system and (*m*) fuzzy rules defined for each input. Therefore, there will be as formidable as m^n fuzzy system rules. In fact, assuming 5 entries is impractical, however to clarify the concept one may examine the system with n=5 and m=3 which then results in 243 rules.

A. *Designing hierarchical fuzzy system:*

The hierarchical fuzzy system is designed such that input variables, instead of being fed into a fuzzy system with high dimensions, which is a common exercise, will be broken in several homogenous fuzzy systems with lighter dimension. As a result, each individual fuzzy system with a moderate dimension forms a surface in overall hierarchical fuzzy system.

Assuming that there are *n* input variable say $x_1, \ldots, x_n$ therefore:

A) The first surface will be a fuzzy system with n_1 variables say $x_1, \ldots, x_n$ with following rules defined:

If x_1 is $A_1^L \ldots$, x_{n_1} is $A_{n_1}^L$ then y_1 is B_1^L

$$2 \leq n_1 < n, L = 1,2,3,m \quad (10)$$

B) i_{th} surface (*i>1*) in a fuzzy system with $(n_i \geq 1)n_i + 1$ is an input variable with the following rules

If x_{N_i+1} is $A^L_{N_i+1}$,x_{N_i+n} is $A^L_{N_i+n_1}$,y_{i-1} is C^L_{i-1}

Then y_i is B^L_i (11)

$N_i = \sum_{j=1}^{i-1} n_j$,*L=1,2,…,M*$_i$

C) Construction of various surfaces continues until i=L such that $\sum_{j=1}^{L} n_j = n$, when all input variables are placed in a surface.

As it can be seen, the first surface $n_1$maps variable x_1, ..., x_{n_1} into variableY_1, which later sent to the second surface. In the second surface, n_2, another variable of $x_{n_1+1}, \dots, x_{n_1+n_2}$ and variable Y_1 are combined and generates another variable called Y_2. Later it also passes to the upper surface. The process repeats till all the variables $x_1, \dots, x_n$ were used up.

In Figure 2 one of the common structures of hierarchical fuzzy systems is depicted.

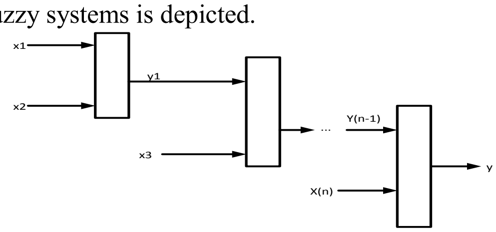

Figure 2. A fuzzy hierarchical structure[24]

Assuming that the fuzzy system contains n inputs and each input contains m members while c is the number of inputs in each surface of a fuzzy system, then one can note:

$$M = \frac{m^c}{(c-1)(n-1)} \quad (12)$$

Since $m^c/(c-1)$ is a constant, it can be seen in equation (12) that the number of hierarchical fuzzy system rules can be increased as the number of input variables increases. Also, it can be easily inferred from the above equation that the fuzzy system contains minimal rules when c=2 [19-26].

V. Cuckoo Optimization Algorithm

Cuckoo Optimization Algorithm was developed in 2011 by Yang,X.S and Deb, S. and later tested Cuckoo Optimization Algorithm into more details [29-31].

As similar to other evolutionary algorithms, COA begins with a primary population, made from cuckoos. The cuckoo population has a number of eggs laid in other birds' nest. Those eggs bearing greater similarity to the host's eggs have a higher chance of being cared for by the host. Eggs that are noticed by the host as being different from their own eggs are perished by the host. The higher the quality of the nest, the more eggs get the chance to turn into grown up cuckoos. Equally, the more eggs capable to grow in an area, the greater number of cuckoos grow up in that region. Therefore, saving more eggs and increasing cuckoo population is an optimization parameter COA [31], [32].

The main reason why Cuckoo Optimization Algorithm works more efficiently than other similar algorithms lies in the fact that COA has a multiple function, such as egg laying and migration.in other types of evolutionary algorithms one can find that functions contain only one particular purpose. In Cuckoo Optimization Algorithm, however, defined parameters follow several functions simultaneously. Unlike other algorithms, in Cuckoo Optimization Algorithm, cuckoos put eggs in various locations. These special egg laying techniques plays two critical roles in the algorithm 1) distribution of eggs around the current optimization point help COA avoid from getting stuck in local optimization. 2) Egg laying process, by its very nature, is a local search process. Other optimization algorithms, however, lack such key function, thus need to be combined with such algorithms as Tabu Search (TS), etc. As a consequence, in COA, convergence occurs at a much faster rate [31-33].

VI. Comparison of Fuzzy Controllers

In control systems, the purpose is to provide a number of features based on quantifiable figures which determine the general function and performance of system. A number of such parameters define system performance, such as (M_p,t_s,t_r,t_p,etc) and others determine steady-state error (e_{ss}), which must be dissolved. In practice, however, using such functions requires trial and error. to obtain appropriate results, it is necessary to select an appropriate performance index. Some of the performance indices are ISE,ITSE,IAE,ITAE,RMSE.

$$ISE = \int_0^{30} [ACE_1(t)^2 + ACE_2(t)^2] dt \quad (13)$$

$$ITSE = \int_0^{30} t * [ACE_1(t)^2 + ACE_2(t)^2] dt \quad (14)$$

$$RMSE = \sqrt{[ACE_1(t)^2 + ACE_2(t)^2]/N} \quad (15)$$

To compare the quality of controllers, three parameters of settling time, maximum oscillation (peak to peak) and three criterions ISE, ITSE and RMS are taken up.

VII. Simulation Results

TABLE I. TWO-AREA SYSTEM DATA

Parameters	Area 1	Area 2
Tg	0.1	0.1
Tt	0.3	0.3
Tr	10	10
Tp	20	20
K1	0.5	0.5
K2	0.5	0.5
B	0.425	0.425
R	2.4	2.4

Table I lists the parameters involved at each area.

A) Design fuzzy-Mamdani controller:

In this paper, all the fuzzy controllers embrace three factors of ACE, ΔACE, and ∫ACE which are input controllers gains proportional, derivative, and integral respectively. Each input falls in the range of [2,-2].“trimf” membership function is selected throughout this work. Other properties of TSK and FUZZY systems are remained intact as portrayed in [1, 2]. To design TSK controller, the output parameters are both set to fixed and linear values. Each control input has three membership functions which becomes $27 = 3^3$.

B) Design fuzzy controller HTSKF

In this fuzzy system the first surface has two inputs of ACE and ΔACE. The output in this surface is blended with ∫ACE which then serves as an input for second surface. Each fuzzy system contains 9 rules that are merged to form 18 rules. It implies that, in a fuzzy system with originally 27 rules can be further amended to obtain 18 rules, which are tantamount to 33% reduction in the number of rules applied. As a consequence, the computational performance of the proposed fuzzy system will be enhanced.

TABLE II. CHARACTERISTICS ALGORITHMS CUCKOO

#	Object	Value
1	numCuckooS	5
2	minNumberOfEggs	2
3	maxNumberOfEggs	4
4	maxIter	100
5	knnClusterNum	1
6	motionCoeff	2
7	Accuracy	0
8	maxNumOfCuckoos	10
9	radiusCoeff	5
10	cuckooPopVariance	1e-13

Table II summarizes the COA algorithm characteristics. The objective function is to minimize the ISE measure drawn in Figure 3 as a way to optimize the rate of changes.

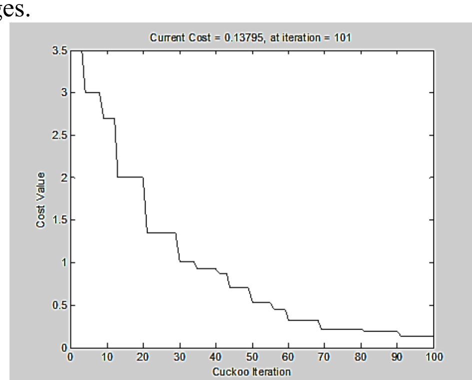

Figure 3 - rate of change of COA Algorithm

To devise an efficient controller the following conditions are in order:

Load disturbance of 8% and 10% took place in areas 1 and 2 respectively and 25% reduction for nominal value experienced [32-34].

Figure 4 shows the frequency deviations in areas 1 and 2 following the situations in state 1 and 2 when no controller adopted in the model.

Both ΔF1and ΔF2 represent almost an identical behavior subject to the conditions set above. The system error in frequencies between two areas was finally curbed although with deep overshoot. The system responses were later improved by placement of the proposed controllers in the LFC model.

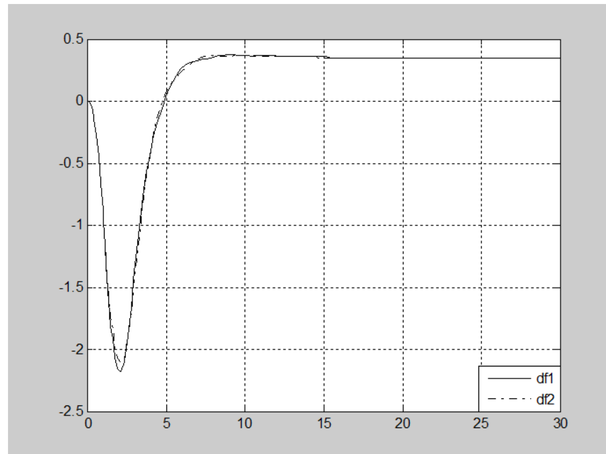

Figure 4- Changes ΔF1and ΔF2 without control systems

Figures 5 and 6, 7 show the frequency deviations in in area 1, area 2, and deviations in power tie-line respectively. One can readily observe that the proposed OHTSKF model outperforms other Fuzzy and TSKF models in terms of response overshoot and executional rapidness. Nevertheless, as compared with other models, implementation of OHTSKF model procures a smoother response and dwindling frequency error closer to zero.

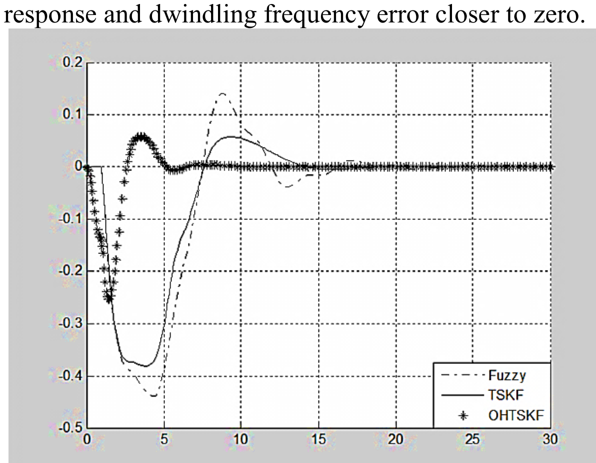

Figure 5- Changes ΔF_1

With the same reasoning, one can explain the system ΔP_tie performance in presence of various controllers as compared with the uncontrolled response in the system. The proposed OHTSKF model outruns others in controlling system with smoother and faster response when the system undergoes the Load disturbance of 8% and 10% took place in areas 1 and 2 respectively and 25% reduction for nominal value experienced. Although the Fuzzy and TSKF represented satisfactory control performances but a great deal of attention needed to pay to the developed OHTSKF model in LFC loop, as it produces a robust solution that ensures the system normal operation to be restored in a more reliable and less noticeably manner.

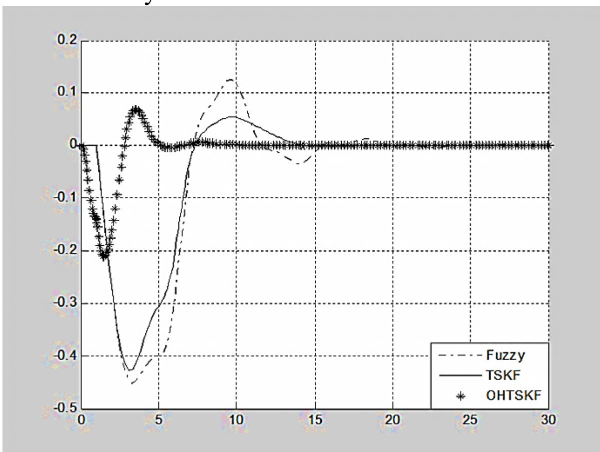

Figure 6- Changes ΔF_2

To further investigate the quality of each controller's solution, Table III is drawn, summarizing ISE measure while different controller implemented in LFC model.

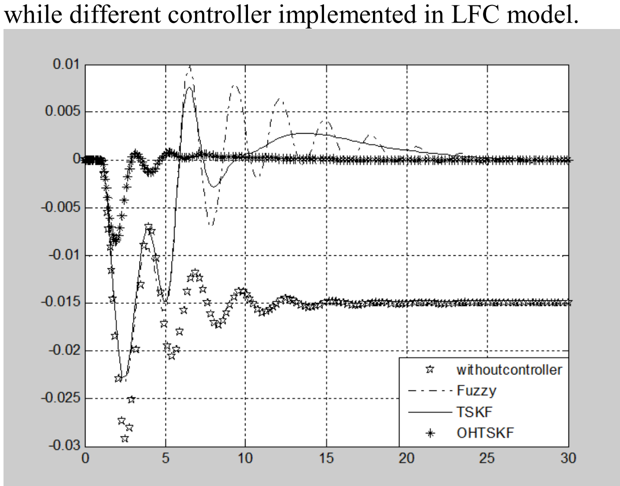

Figure 7- Changes $\Delta \mathbf{P_{tie}}$

These measures aimed at determining the accuracy of each controller to tackle abrupt disturbances in frequencies of interconnected areas as well as tie-line power transfers.

TABLE III. COMPARISON OF ISE CRITERION

Controller	ISE Criterion
Without Controller	12.423
FUZZY	0.7443
TSKF	0.599
OHTSKF	0.1631

As can be seen in Table III, the proposed OHTSKF model outpaced others with smaller ISE error, in other words, higher accuracy. In this sense, the developed OHTSKF represents 0.1379 ISE as opposed to TSKF with 0.29 and Fuzzy with 1.61 ISE errors subject to the prescribed loading conditions in two areas.

TABLE IV. COMPARISON OF ITSE CRITERION

Controller	ITSE Criterion
Without Controller	62.8173
FUZZY	3.1821
TSKF	2.4716
OHTSKF	0.2486

Tables IV and V reiterate the fact that the OHTSKF model outweighs others while other standard error minimization criteria such as ITSE and RMS were applied.

TABLE V. COMPARISON OF RMS CRITERION

Controller	RMS Criterion
Without Controller	0.2202
FUZZY	0.0128
TSKF	0.0088
OHTSKF	0.0026

Tables VI-VIII provide the transient simulations when 2% band for standard settling time is considered Taking into account each controller performance shown in consecutive Tables VI-VIII, represents that the proposed OHTSKF controller technique delivers proper control actions containing shorter settling time and flexible peak to peak (P-P) maximum oscillations.

TABLE VI- COMPARISON OF THE RESULTS $\mathbf{\Delta F_1}$

Controller	Settling Time	Max.Oscillation(p-p)
Without Controller	13.1571	2.5538
FUZZY	13.7539	0.5810
TSKF	12.3289	0.4402
OHTSKF	4.5604	0.3120

However, the proposed hierarchical fuzzy systems which later optimized by COA algorithm were preferred as it eliminates superfluous fuzzy rules in a way to obtain the same control actions but in efficient settling time and denser oscillation overshoots.

From the Tables VI-VIII, one can find that settling time and peak to peak oscillations for the OHTSKF is more efficient than the other three contenders.

TABLE VII. COMPARISON OF THE RESULTS ΔF_2

Controller	Settling Time	Max.Oscillation(p-p)
Without Controller	13.6936	2.4782
FUZZY	14.6990	0.5773
TSKF	12.3289	0.4812
OHTSKF	4.3683	0.2797

In this sense, as in Table VI, OHTSKF meets the stable response and minimized error at 4.5 s while TSKF and Fuzzy Mamadani controllers hit stabilized in 12.32 s and 13.75 sec respectively, that is, implies nearly 63% and 67.3% improvements in system settling time if OHTSKF takes over the LFC control. Similarly, maximum peak to peak oscillations for each controller represents that OHTSKF model offers less oscillations in the response to be died out, whereas other controllers seemingly show an inferior response with the same conditions. From Tables VI-VIII, the P-P max oscillations for OHTSKF, TSKF, and Fuzzy Mamdani are 0.31, 0.44, 0.58 respectively that emphasizes 29.5%, 46.5% enhancement in the system oscillations if one is using the proposed OHTSKF controller.

TABLE VIII. COMPARISON OF THE RESULTS ΔP_{tie}

Controller	Settling Time	Max.Oscillation(p-p)
Without Controller	5.4184	0.0292
FUZZY	2.7318	0.0331
TSKF	2.5986	0.0305
OHTSKF	0	0.0093

VIII. CONCLUSION

An optimal model for Load-Frequency Control in was proposed. An Optimized Hierarchical Takagi Sugeno Kang Fuzzy (OHTSKF) was developed to improve the fuzzy Mamdani and TSKF control performances. OHTSKF breaks down Fuzzy Mamadani systems into several sub-systems, then reducing the number of fuzzy rules. This speeded up the computational performance. After that, Cuckoo Optimization Algorithm (COA) integrated into the model to improve response errors for the proposed OHTSKF. The simulation results indicated that the developed OHTSKF controller is highly efficient as compared with other controllers. Based on the results, the proposed model can supersede current Fuzzy Mamdani and TSKF controllers in LFC loops in realistic applications.

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