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Inserting of heuristic techniques into the stability regions for multiarea load frequency control systems with time delays

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Abstract: The design and optimization of robust controller parameters are required to improve the controller performances and to keep the stability of load frequency control (LFC) system. In addition, reducing the number of iterations and computational time is very important for swiftly tuning of the controller parameters and the system to reach stability rapidly. For this purpose, this study presents the inserting of heuristic optimization techniques into stability regions method identified in proportional-integral (PI) controllers space for multiarea LFC systems with communication time delays (CTDs). This method consists of two steps: determination of stability region for the system and application of heuristics. Stability region for the system is found via stability boundary locus (SBL) and moth-flame optimization (MFO), particle swarm optimization (PSO), sine cosine algorithm (SCA), slime mould algorithm (SMA) and whale optimization algorithm (WOA) are inserted and applied to this region. In addition, a cost function having time domain specifications is developed for improving the performances of LFC and it is compared with the well-known integral error functions. Also, the robust stability region, which tolerates any system parameter and any time delay variation, is identified and the significance of this region is given for robustness analysis. It is observed from the analyses that better system outputs have been obtained with developed cost function. Steady state errors are minimized and transient state performances are improved with the proposed method. Moreover, desired system performances have been achieved with lower computational time and iteration number (approximately more than about 89% reduced according to classical approach) without deteriorating the stable structure of the system by the proposed method.

Key words: Load frequency control, optimization in stability regions, heuristic techniques, objective function, communication time delays

1. Introduction

Modern electrical power systems consist of multiple controllable areas connected by interconnected tie-lines. Uninterrupted, safe and stable operation of electrical power systems is very important for both consumers and supplying companies [1]. From this perspective, load frequency control or automatic generation control (AGC)

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has a very vital importance for reliable operations of power systems. LFC is a very complex and difficult issue for electric power systems due to multiple control areas. The basic idea of LFC system is defined as follows: i) to make frequency deviations zero by regulating each control area, and ii) to make the power deviation of the interconnected tie-line to zero [2].

With the utilization of communication networks, time delay problems are unavoidable for LFC mechanism due to several reasons such as packet losses, faults of communication channels and extensive data transfer between central controller and generation units [3–5]. Although the integration of communication networks into LFC systems is required to receive the frequency measurements and transmit the control signals, the observed time delays severely degrade the controller performance and could lead to instability, decreasing the damping effect of LFC systems [4–6]. Therefore, considering the time delays for stability assessment in LFC systems, the design of proper controller parameters against the uncertain communication delays is important to increase the controller performance and system stability.

Since the recent studies in the literature related with LFC examine in detail, it can be seen that various optimization techniques, objective functions and controller types are used for find better performance results of the system. Most of these studies, a random parameter space has been defined and the control parameters of the system have been tried to be found from this space. In 2015, Abdelaziz et al. used cuckoo search algorithm (CSA), particle swarm optimization (PSO) and genetic algorithm (GA) for analyzed three area power system [7]. Integral time absolute error (ITAE) selected as objective function and controller parameter space range is chosen [–2, 2]. Sambariya et al. applied elephant herding optimization (EHO) and integral square error (ISE) function to single area power system in 2017. In order to define search space, controller gain range selected as [7, 9] for K_P, [3, 5] for K_I and [3, 4] for K_D [8]. Mudi et al. used multiverse optimization algorithm (MVO) and ITAE function for tuning of 3DOF-PID controller in 2019 [9]. The controller parameters space range was selected between [1, 4] for this study. Celik used dragonfly search algorithm (DSA) and ITAE function for tuning cascade FOPI-FOPD controller parameters for advanced load frequency control in 2020 [10]. In this study, Celik selected controller gain parameters for some cases between [0, 3] and another cases between [–2, 2] and fractional coefficients of controller between [0, 1.5] for all cases. Khokhar et al. applied salp swarm optimization algorithm (SSO) and ISE function for tuning of cascade PI-PD controller in 2020 [11]. The controller gain parameters range was chosen between [–5, 5] and [40, 120] for filter coefficient. In the same year, Veerasamy et al. performed hybrid particle swarm optimization-gravitational search algorithm (PSO-GSA) optimization technique for the minimization of the integral absolute error (IAE) function to find more efficient results. Cascade PI-PD controller parameter ranges were selected in the range of [–100, 10] with a few trial runs [12]. Latif et al. used different heuristic techniques and ISE function for tuning of PI-(1 + PD) controller in 2021 [13]. The controller parameters range was chosen between [0, 250]. When these and similar studies in the literature are analyzed, it is clearly seen that there is no clear range in the selection of the parameter space of the controller.

Because stability regions offer a complete analysis with optimum parameter selection, these are very important for LFC systems. Stability regions for the system are found for PI controller via SBL method in this study. SBL method is a frequency-based graphical method and presented by Tan et al. [14]. This method is only used to calculate PI controller parameters guaranteeing Hurwitz stable and marginally stable conditions. It can be noted that, if selected parameter space does not cover the stability region, the parameters that make the LFC system stable can never be found. It means that the system is always unstable for all assigned control parameters via heuristic methods. In addition to these, if controller parameter space covers the part of the stability region, appropriate solutions may not be found for the system. In this case, the system can exhibit bad performances. Additionally, fast tuning of controllers is very important to quickly stabilize the system. In this way, it is ensured that the system remains unstable or in poor performance in less time. Thus, the numbers of iterations and candidate solutions at the heuristic methods in processing period are two important parameters. The increase of these also increases the computation time of the methods. In this situation, controllers are tuned very late and so it takes longer for the system to reach optimum performance. In addition to the mentioned disadvantages, using objective function has significantly affected the system outputs. Because it is used in the heuristic methods for tuning of controller parameters.

Based on the above discussion, an efficient way of selecting the search space in the controller gain space and an effective objective function are required to improve the optimization procedure before applying any optimization technique to LFC systems. In order to eliminate the mentioned disadvantages, inserting of heuristic techniques into the stability regions method is proposed for LFC systems in this study. The proposed approach includes the following two steps: Identification of stability regions in the PI controller space using SBL method and inserting of the various heuristic methods to determine the optimal PI gains inside the stability region. In addition to this approach, a different objective function having time domain specifications is developed and used in the heuristic techniques for improved the LFC system outputs. The main contributions and differences of this work could be stated as follows:

- Heuristic methods are inserted into the stability region of LFC system and so transient performances are improved and steady state errors are minimized.
- Stability of the LFC system is ensured for all random control parameters assigned by heuristic methods throughout the iteration process.
- An objective function is developed, including time-domain specification. Thus, system performances are improved.
- The desired system performances are achieved with less iteration number and computational time (both of them are reduced by about 89% compared to classical approaches) with the proposed method.
- The robust stability region and the importance of this region are shown by taking into account the changes in system parameters and time delays at different rates.

The rest of the paper is organized as follows: Section 2 presents the dynamical model of LFC system having time delay and effect of stability regions to the system stability. In Section 3, heuristic optimization algorithms are briefly overviewed. Then, developed objective function is mathematically expressed and the motivation of the proposed inserting of heuristics into the stability regions method is explained. Effectiveness of proposed objective function and proposed method are shown comparatively and results are given in Section 4. Moreover, robust stability region and its importance is given for robustness analyses in the same section. Finally, assessments and conclusions of this paper are given in Section 5.

2. Dynamical model of time delayed LFC

Multiarea power systems have a complex nonlinear structure. Because of the slow convergence rate, it can be considered and modeled linearly for load frequency control [15]. However, communication time delays occur mostly due to the communication components in the system. These delays are formed from such as phasor measurement units (PMUs), remote control center, geographical conditions. These time delays negatively affect the effectiveness of the controller and also decrease the system performances [16]. For this reason, CTDs must be included in the LFC model to achieve the near realistic performances. System model of N-control area power system having CTDs is shown in Figure 1:

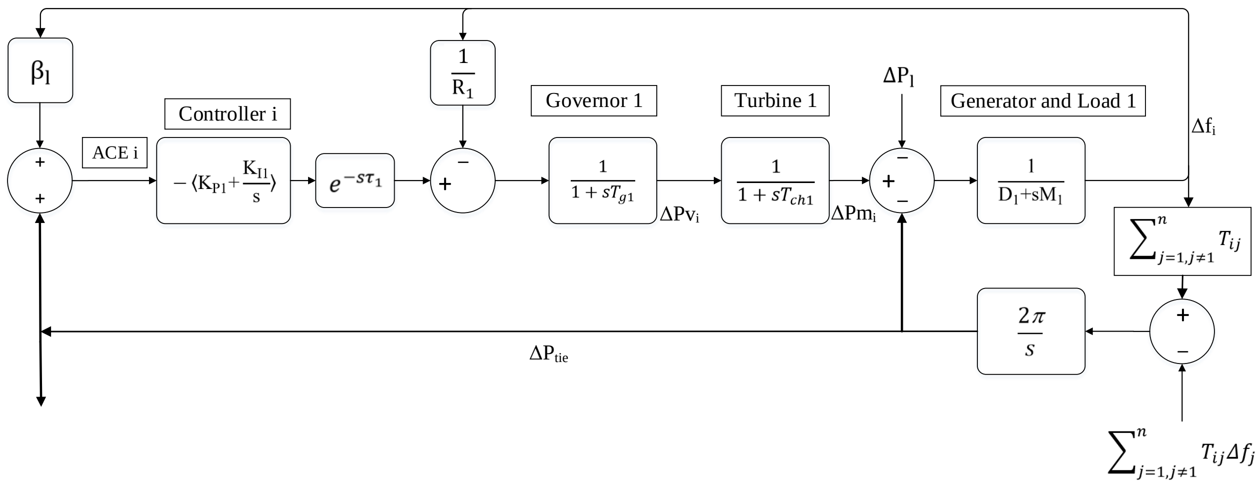

Figure 1. N-area interconnected power system model with time delays.

T0 implement the proposed approach to the LFC system, controller stability regions must be calculated. For this reason, characteristic equation of the system must be calculated. In this study, PI controller is selected for shown superior effect of the proposed strategy and characteristic equation is found for this controller. The dynamics of LFC system are defined by the following state-space equation model:

$$\dot{x}(t) = Ax(t) + Bu(t) + \Delta Pd \tag{1}$$

$$y(t) = Cx(t)\ . \tag{2}$$

In here, x is a state vector and has [k × 1] dimension, u is a control vector and has [g × 1] dimension and y is an output vector and has [r × 1] dimension. A, B, and C are constant matrices and their dimensions are [k × k], [k × g], and [r × k], respectively.

For multiarea LFC systems following vectors are defined:

$$x_i(t) = \begin{bmatrix} \Delta f_i & \Delta Pm_i & \Delta Pv_i & \int ACE_i & \Delta P_{(tie-i)} \end{bmatrix}^T \tag{3}$$

$$y_i(t) = \begin{bmatrix} ACE_i & \int ACE_i \end{bmatrix}^T\ . \tag{4}$$

In LFC model ACE signal is defined as follows:

$$ACE_i = \beta_i \Delta f_i \pm \Delta P_{(tie-i)}\ . \tag{5}$$

Since the ACE signal has a delay and ACE is input to the PI controller, the PI controller is selected as follows:

$$u_i(t) = -K_{Pi} ACE_i - K_{Ii} \int ACE_i = -K_i y_i(t-\tau_i) = -K_i C_i x_i(t-\tau_i) \ . \quad (6)$$

Equation of dynamic model closed loop system is given as follows:

$$\dot{x}(t) = Ax(t) + \sum_{i=1}^{n} A_{di} x(t-\tau_i) + F\Delta Pd \ . \quad (7)$$

In here, $A_{di} = \text{diag}[0 \ ... \ -B_i K_i C_i \ ... \ 0]$ and $K_i = [K_{Pi} \ \ K_{Ii}]$. Using these equations, characteristic equations are determined for the related power system. For example, characteristic equations for single and two-area power system are found as follows:

$$\Delta(s,\tau) = det\left[sI - A - A_d e^{-s\tau}\right] = a_0(s) + a_1 e^{-s\tau} = 0 \quad ; \quad for\ single\ area \quad (8)$$

$$\Delta(s,\tau_1,\tau_2) = b_0(s) + b_1(s)e^{-s\tau_1} + b_2(s)e^{-s\tau_2} + b_3(s)e^{-s(\tau_1+\tau_2)} = 0 \quad ; \quad for\ two-area. \quad (9)$$

For these equations, the degree of a_0 and a_1 polynomials is 4 and 1, respectively and the degree of b_0, b_1, b_2 and b_3 polynomials is 9, 6, 6, and 3, respectively. To obtain stable regions according to the PI controller, jw is written instead of s in the characteristic equations. These equations have exponential terms due to communication time delays. This term is written as follows:

$$e^{-s\tau_i} = e^{-jw_i\tau_i} = cos(w_i\tau_i) - jsin(w_i\tau_i) \ . \quad (10)$$

Real and imaginary parts of characteristic equations are defined and equaled to zero separately. After then, obtained equations are solved according to controller parameter and so related stability regions are found.

In this study, communication time delays in the regions are selected as $\tau = 1.4$ s. By solving characteristic equations, stability regions of single area and two-area power systems are found and given in Figure 2. In order to clear illustration, crossing frequency is chosen as $w_c \ \epsilon \ [0\text{-}2.50]$, where CRB is complex root boundary and RRB is real root boundary.

It can be clearly seen from Figure 2 that multiarea systems have more than one region. For this or similar situation, innerregion guarantees system stability for all controller parameters. In order to clear understanding, the effect on stability of the system according to the stability region is analyzed considering the right side of Figure 2 and it is illustrated in Figure 3.

In Figure 3; selected controller parameters are inside the CRB1 ($K_P = 0.2$, $K_I = 0.75$), on the CRB1 ($K_P = 0.2$, $K_I = 0.76$) and outside the CRB1 ($K_P = 0.2$, $K_I = 0.77$) (note that this point is inside the CRB2). For ($K_P = 0.2$, $K_I = 0.75$) inside the CRB1, the LFC system is stable due to the decaying oscillations. For (K_P=0.2, K_I=0.76) on the CRB1, the sustained oscillations of the system frequency illustrate marginally stable behavior of the LFC system. Finally, for (K_P=0.2, K_I=0.77) outside the CRB1, the increasing oscillations of the system frequency indicate the unstable behavior of the LFC system, verifying the unstable boundary of CRB2.

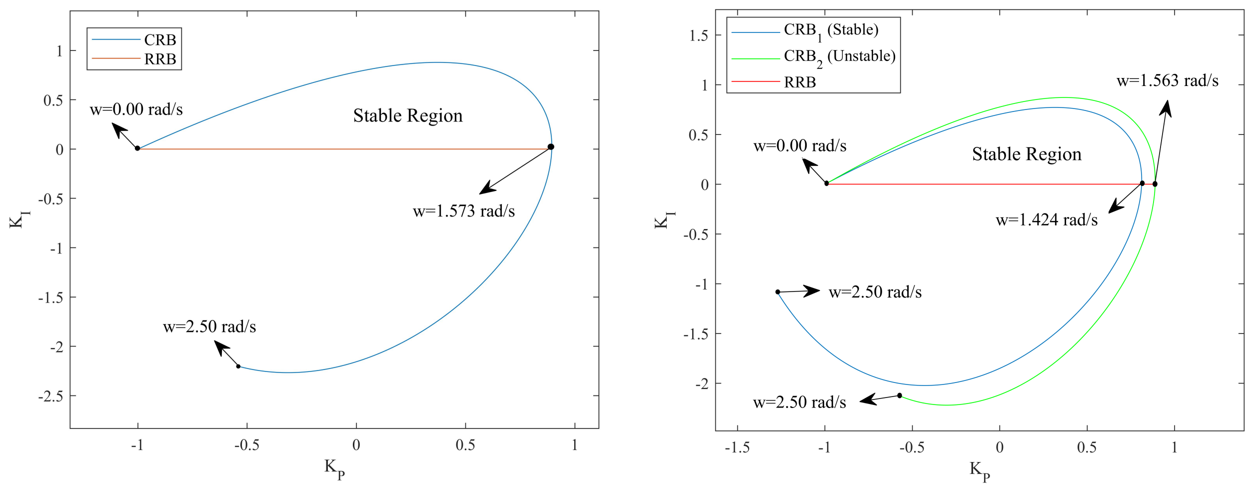

Figure 2. Stability regions of power systems; for single area (left), for two-area (right).

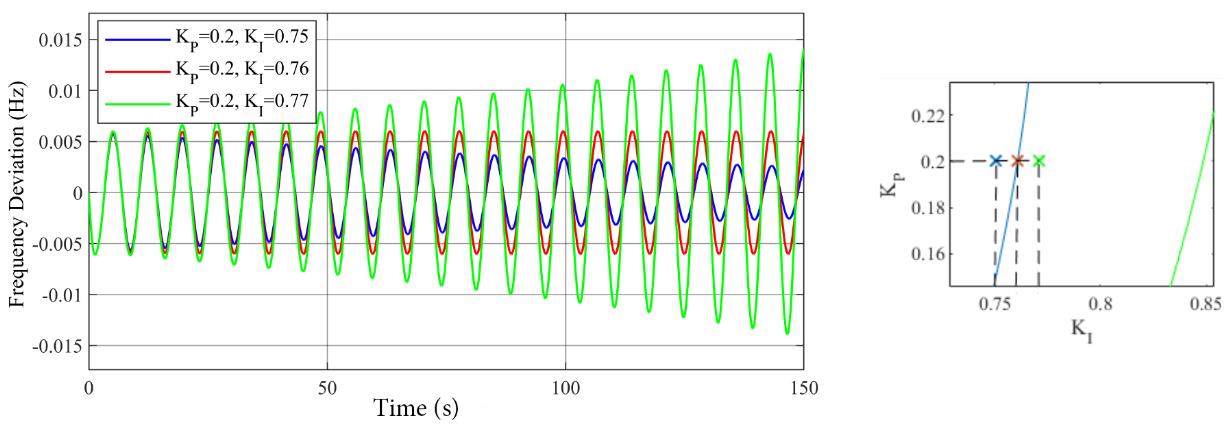

Figure 3. Frequency responses for the selected controller gains (left), selected controller gains (right).

3. Material and methods

In this section, general overview of heuristic techniques, developed objective function and proposed approach to the LFC systems are explained.

3.1. Process of heuristic techniques

Heuristic methods are very useful especially for complex engineering and optimization problems. Heuristic techniques try to find the most suitable solution for the system with their different convergence behaviors. These methods generally generate random candidate solutions in order to reach the global best solution. All randomly generated candidate solutions are evaluated in every iteration. The best iteration solution is determined from these. This best iteration solution is compared with the best solution so far (best global solution). If the best iteration solution is better than the best global solution, the best iteration solution is assigned as the best global solution. However, if the best global solution is better than the current best iteration solution, the best global solution is kept at the same value. This iterative process continues until the termination criteria are met. General running procedure of heuristic techniques is shown in Figure 4.

In the present study, moth-flame optimization (MFO) [17], slime mould algorithm (SMA) [18], particle

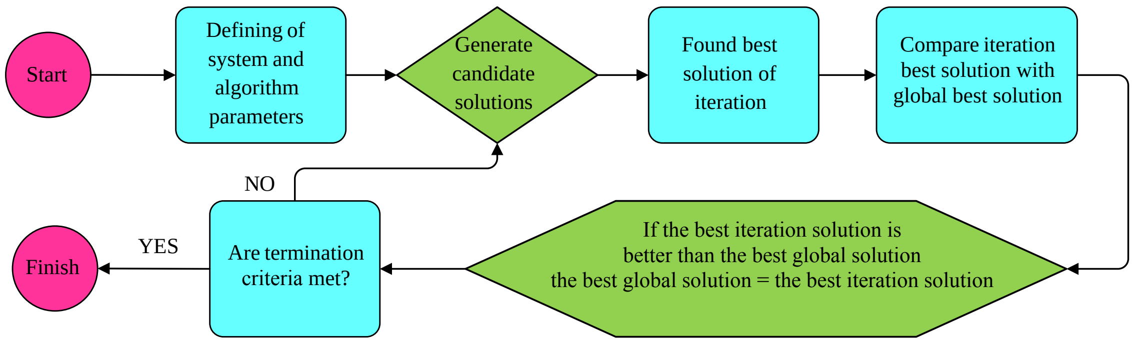

Figure 4. Basic flow chart for process of heuristic algorithms.

swarm optimization (PSO) [19], whale optimization algorithm (WOA) [20] and sine cosine algorithm (SCA) [21] heuristic techniques are applied to two-area LFC model in order to show the effectiveness of proposed method. The reasons of selecting these heuristic optimization techniques are briefly explained as follows:

- MFO algorithm is a very successful technique for the undefined search space.
- PSO is one of the well-known methods and it has been applied to many different problems. Thus, its success has been proven for many studies.
- SCA can explore different regions of the search space and thus it can be an effective use of the search space. For this reason, it can be effective for undefined search space.
- SMA has an outstanding balance between exploitations and explorations. Therefore, the tendency to find better results is high.
- WOA has a good exploration, exploitation and convergence behavior and so it can avoid a local optima.

When the literature is examined, it is possible to find many optimization algorithms. Since the behavioral features of optimization techniques are approximately similar to each other, the number of selected algorithms is considered sufficient to show the superiority of the proposed approach. In the proposed method, by applying heuristic methods within the stability region for the system, it is guaranteed that the system remains stable for all candidate solutions and the desired system performances are achieved very quickly.

3.2. Developed objective function

In order to obtain better system performances for LFC, different objective functions are used in the heuristic techniques. When the recent studies in the literature are examined, the most well-known integral error functions (integral absolute error (IAE), integral time-weighted absolute error (ITAE), integral squared error (ISE), integral time-weighted squared error (ITSE)) are selected and applied [22–25]. These integral error functions only use error value and the main goal is to minimize the output signal error. The usage of error values of output signals only might be inadequate to obtain better system performances. Settling time and overshoot of output signals are very important two parameters for a load frequency control. In order to improve system dynamics performances considering with time domain outputs, a different objective function is developed in this paper. In addition to the error values, time domain specifications of the frequency and tie-line power response are included in the proposed objective function and it is given as follows:

$$OF = \sum_{i=1}^{Z} a_i \int_0^T t|e_i(t)dt| + \sum_{i=1}^{Z} b_i ST_i + \sum_{i=1}^{Z} c_i OS_i \ . \tag{11}$$

where Z is total region and tie-line number, a_i, b_i and c_i are weighted coefficients, ST_i is settling time and OS_i is overshoot value of the output signals related with frequency deviations or tie-line power deviations (i = 1, 2, ... Z). Moreover, it is mentioned in [1] that ITAE has a tendency improve of system performance results. For this reason, ITAE is selected in this function to minimize the output error value.

3.3. Inserting of heuristics into the stability region for LFC

In heuristic-based methods, a user-defined control parameter space is formed while determining the optimal controller parameters. In this process, algorithms search the entire parameter space defined by the user. In this approach, heuristic techniques try to find the solutions from stable and unstable regions. If user-defined search space does not cover the stability region, solutions that ensure system stability cannot be found and thus system will never be stable. If the randomly selected search space covers a part of the stability region or it covers larger than stability region, the desired results may either not be found or take too long time to be found.

For the reasons mentioned above, the algorithm(s) may show a poor convergence behavior and bad search performances. In addition, in order to find better solutions, computational time and iteration number of algorithm can intensely increase for multiarea power systems. To overcome these disadvantages and to ensure that the system remains stable, inserting heuristics into the stability region method is proposed for LFC.

In order to make easy to understand of impact and efficiency of the proposed method, a random user-defined control parameter space is defined. The boundary of controller space is chosen as K_P [+5,–5] and K_I [+5,–5]. Behavior of heuristic algorithm for user-defined search space and distributed of candidate solutions (CSs) via heuristic method is shown in Figure 5.

As can be clearly seen from Figure 5, very few of the assigned candidate solutions are in the stability region, which will make the system stable. Therefore, very few candidate solutions ensure the stability of the system. In addition, while these candidate solutions keep the system stable, the system outputs may not be as desired because fewer solutions are used. At this point, the superiority of the proposed method comes to the fore. Figure 6 shows the graphic obtained by applying heuristic algorithms into the stability region.

It is clear from Figure 6 that all possible candidate solutions assigned by the heuristics lie within the stability region. Thus, the stability of the system is ensured for all assigned solutions. Moreover, many of CSs are swiftly convergence to minimum point according to the objective function. For this reason, the most suitable control parameters, which provide the desired system performance, are achieved very fast and guaranteeing the stability of the system.

4. Results and discussion

The efficiency and superior success of the proposed method and the objective function are shown comparatively for two-area power system with time delays using MFO, PSO, SCA, SMA, and WOA heuristic techniques. System analyses have been examined in terms of overshoot (OS), undershoot (US), settling time (for 0.005% bandwidth), and peak to peak (PtP) values.

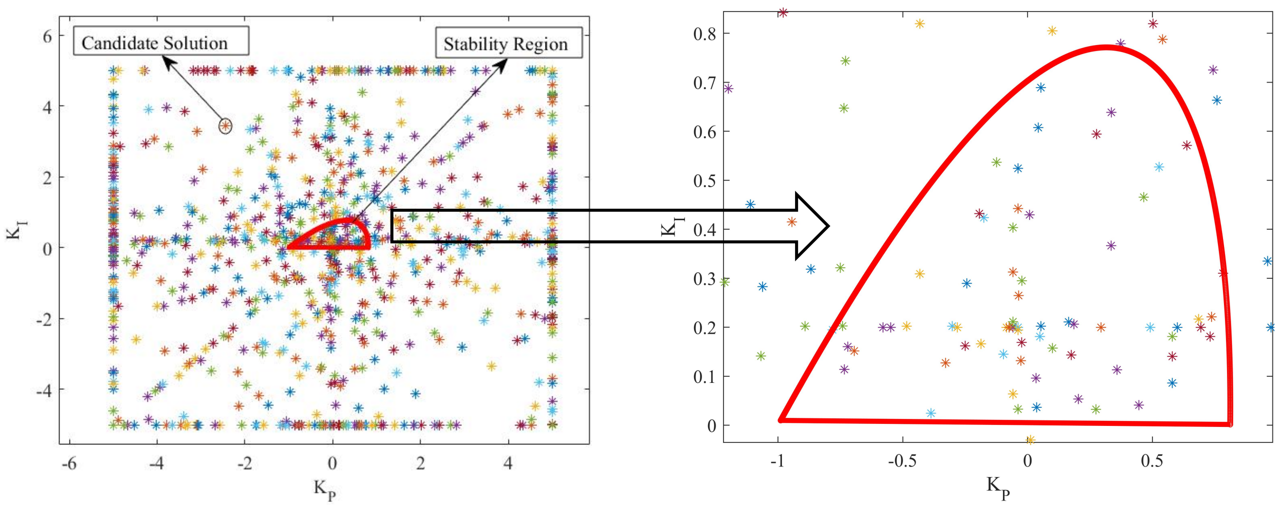

Figure 5. Distribution of CSs; all CSs in search space (left), CSs within the stability region (right).

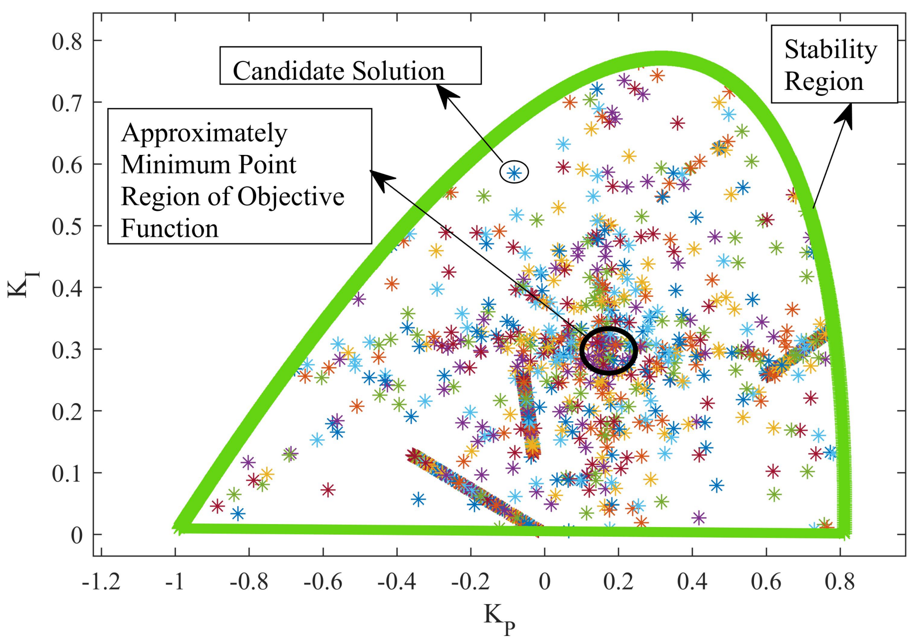

Figure 6. Distribution of CSs in stability region.

4.1. Comparative performances of proposed objective function

In this section, efficiency of developed objective function is analyzed and compared with well-known integral error functions. SMA is applied to two-area power system in order to show an impressive performance of proposed function. System parameters for two-area system are given in Appendix. Iteration number and population size are chosen 50 and 20, respectively. In addition, 0.1 p.u. MW step load disturbances are applied from both area-1 and area-2 at t = 0 s. It can be noted that, results are calculated in a user defined controller parameter space (K_P [–5, +5], K_I [–5, +5]). Figure 7 gives comparative results of the frequency deviations and deviation in the tie-line power exchange. It can be clearly seen that smooth and better output signals have been obtained for regions and tie-line with proposed objective function.

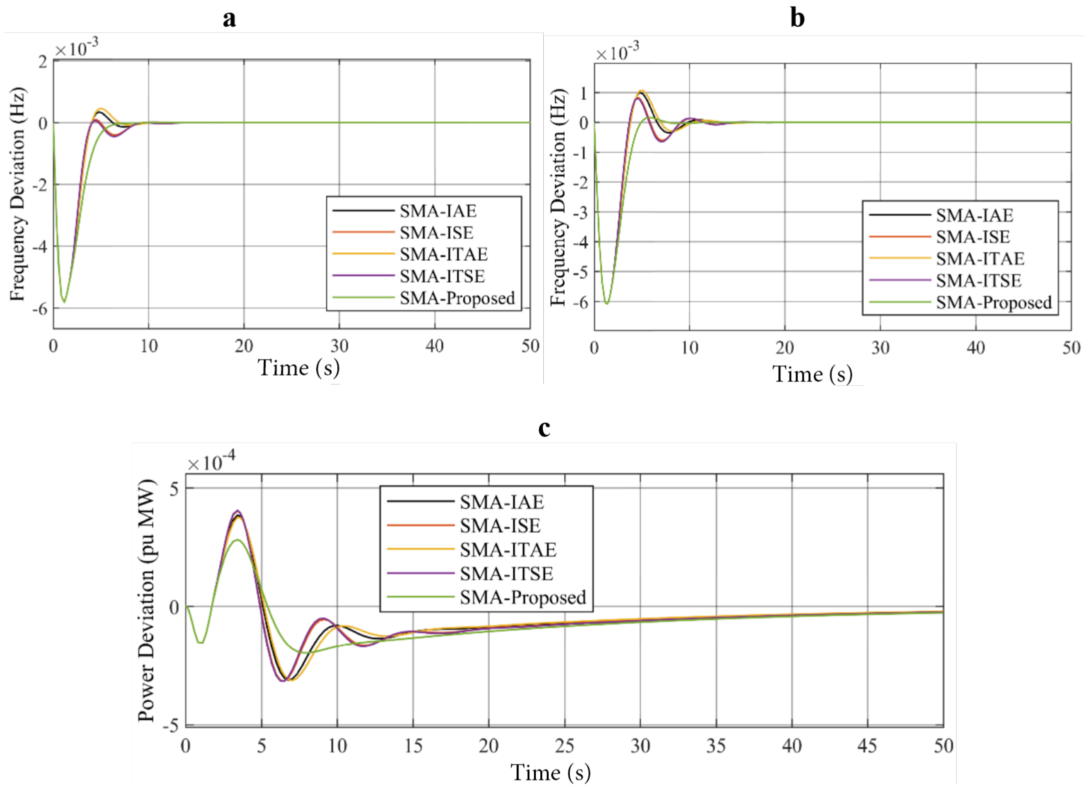

Figure 7. Deviations; a) frequency of area-1, b) frequency of area-2, c) power of tie-line.

System performance results according to objective functions are given in Table 1.

Since the time domain specifications of output signal values (settling time and overshoot) are taken into account with the proposed function, these output signals are improved at the same time while minimizing the signal error values. When analyzed from Table 1, all system performance results have been found lower values with proposed objective function than compared well-known integral error functions except settling time of tie-line. Lower overshoot values are found as 6.268e-6, 1.634e-4, and 2.826e-4, respectively, for area-1, area-2, and tie-line with proposed objective function. Also, it can be clearly seen that, peak to peak values of the outputs signal are found lower than integral error functions. Moreover, except for tie-line, lower settling times of area-1 and area-2 calculated as 6.529 and 7.108, respectively. Since better results are obtained with the proposed objective function, it is used in the next sections' analyses.

4.2. Analyses of proposed method for LFC

In this section, two-area power system having communication time delay is analyzed with proposed inserting of heuristics into the stability region method. The proposed approach is illustrated in Figure 8.

For this system, overshoot and settling time values are two very important factors and it is desirable that these are at low values. Therefore, specific overshoot and settling time have been determined as termination criteria. Considering the system dynamics and controller performances, the termination criteria in this study are specified as follows: ST of area-1 is lower than 15 s and OS is lower than 3e-5; ST of area-2 is lower than 15 s and OS is lower than 3e-5; ST of tie-line is lower than 45 s and OS is lower than 3e-4. In this way, superiority of proposed approach is proven with the results in Table 2.

Table 1. Objective functions results.

Area-1				
Function	OS	US	ST (<=0.005%)	PtP
IAE	3.366e-4	-5.810e-3	8.771	6.146e-3
ISE	1.030e-4	-5.810e-3	8.638	5.913e-3
ITAE	4.495e-4	-5.810e-3	8.995	6.259e-3
ITSE	6.179e-5	-5.810e-3	8.654	5.871e-3
Proposed	6.268e-6	-5.810e-3	6.529	5.816e-3
Area-2				
Function	OS	US	ST (<=0.005%)	PtP
IAE	1.001e-3	-6.085e-3	11.911	7.086e-3
ISE	8.325e-4	-6.085e-3	13.678	6.917e-3
ITAE	1.080e-3	-6.085e-3	12.262	7.164e-3
ITSE	8.054e-4	-6.085e-3	13.663	6.890e-3
Proposed	1.634e-4	-6.085e-3	7.108	6.248e-3
Tie-line				
Function	OS	US	ST (<=0.005%)	PtP
IAE	3.853e-4	-3.101e-4	31.238	6.955e-4
ISE	4.040e-4	-3.153e-4	33.130	7.193e-4
ITAE	3.758e-4	-3.125e-4	30.566	6.882e-4
ITSE	4.055e-4	-3.145e-4	33.507	7.201e-4
Proposed	2.826e-4	-1.963e-4	35.729	4.789e-4

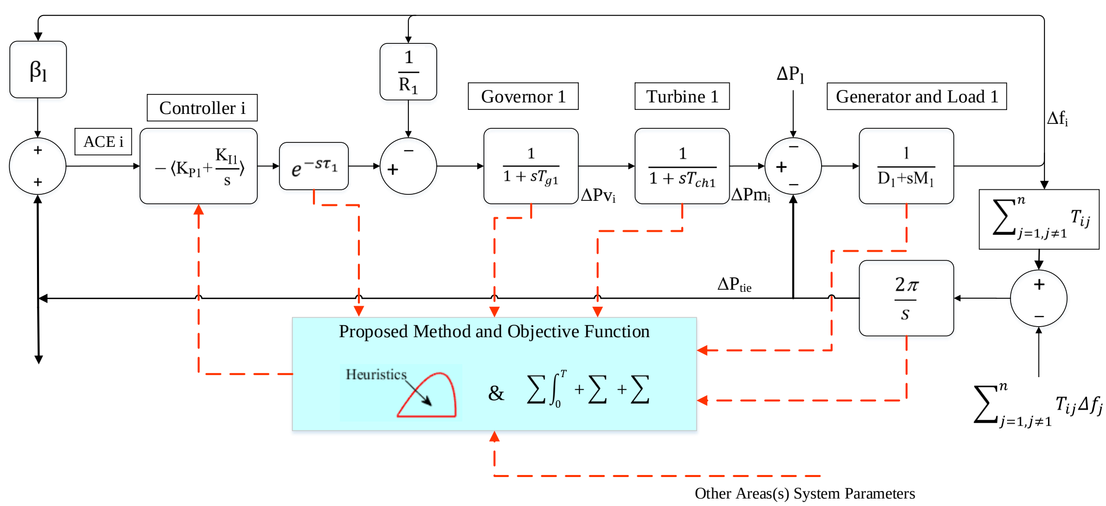

Figure 8. Illustration of the proposed method.

Obtained controller parameters, computational times (as second) and the number of iterations when the termination criteria are met are given in the Table 2. In this table, performed analyses in the stability region are expressed as in SR.

With the proposed method, only the region that can keep the system stable is processed. Since the heuristic methods search the optimal solution within this stable region, the desired performances for the system are obtained very fast. It can be clearly shown from results presented in Table 2 that computational time

Table 2. Controller parameters and performances of proposed method for two-area power system.

Method	Ki	Kp	C. time	Iter.	Method	Ki	Kp	C. time	Iter.
MFO in SR	0.2399	0.0670	213.848	3	MFO	0.2805	0.1181	1988.131	19
PSO in SR	0.2896	0.1937	214.746	3	PSO	0.2735	0.1909	4516.954	60
SCA in SR	0.2396	0.0509	219.246	3	SCA	0.2675	0.2018	1068.355	15
SMA in SR	0.2840	0.1310	214.696	3	SMA	0.2600	0.1476	1278.660	18
WOA in SR	0.2886	0.1444	139.849	2	WOA	0.2721	0.2079	1125.154	16

and iteration number are dramatically reduced with the proposed method. Average computational time is calculated 200.477 s for proposed approach (within SR) and 1995.451 s for classical approach (without SR). Similarly, average iteration number is calculated 2.8 for proposed approach (within SR) and 25.6 for classical approach (without SR). From these average results, computational time is decreased approximately 89.95% and iteration number is reduced approximately 89.06%.

Comparative frequency deviations for both regions and power deviation of tie-line are illustrated in Figure 9. Moreover, numerical performance analyses within and without stability region are given in Table 3.

Heuristic methods are converged to same undershoot values for area-1 (US = 5.810e-3) and area-2 (US = -6.077e-3) because of using system and controller dynamics. It can be noted that for the second region in Table 2, showing the overshoot values as 0.000e-0 means that the algorithms do not performed overshoot for the defined time range. When analyzed together with the results given in Tables 2 and 3, the obtained results showed that the proposed method is found the optimal results more easily and very quickly than the classical method.

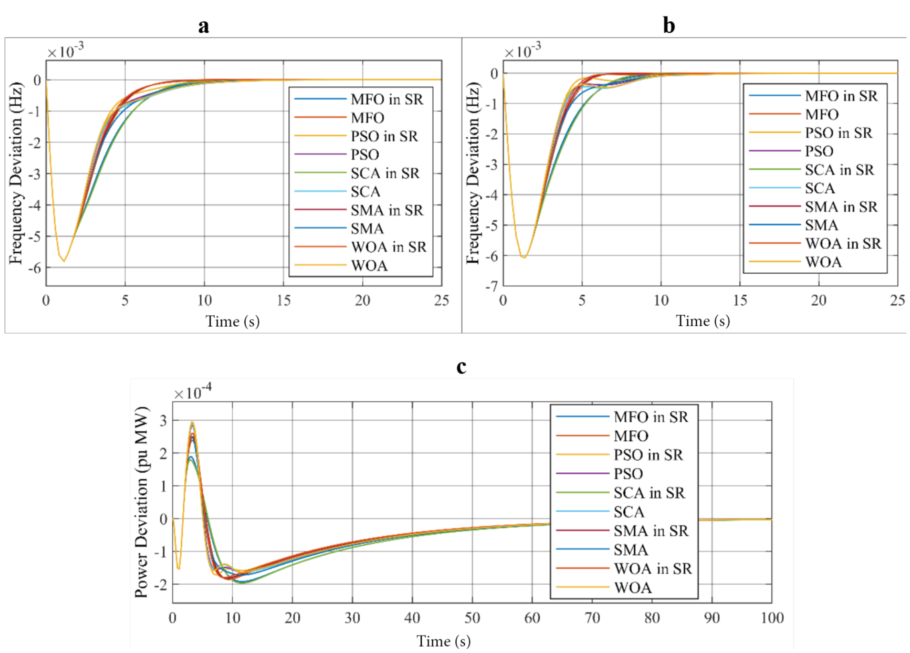

Figure 9. Deviations; a) frequency of area-1, b) frequency of area-2 frequency, c) power of tie-line .

Table 3. Results for area-1, area-2, and tie-line.

Area-1				
Method	OS	US	ST(<=0.005%)	PtP
MFO in SR	6.899e-6	-5.810e-3	10.246	5.817e-3
MFO	7.050e-6	-5.810e-3	7.928	5.817e-3
PSO in SR	4.852e-6	-5.810e-3	10.173	5.814e-3
PSO	4.607e-6	-5.810e-3	11.371	5.814e-3
SCA in SR	1.004e-5	-5.810e-3	9.554	5.820e-3
SCA	4.341e-6	-5.810e-3	12.162	5.814e-3
SMA in SR	6.382e-6	-5.810e-3	8.225	5.816e-3
SMA	5.042e-6	-5.810e-3	11.286	5.815e-3
WOA in SR	6.012e-6	-5.810e-3	8.473	5.816e-3
WOA	4.339e-6	-5.810e-3	11.944	5.814e-3
Area-2				
Method	OS	US	ST(<=0.005%)	PtP
MFO in SR	0.000e-0	-6.077e-3	9.567	6.077e-3
MFO	1.249e-6	-6.077e-3	6.347	6.078e-3
PSO in SR	0.000e-0	-6.077e-3	9.946	6.077e-3
PSO	0.000e-0	-6.077e-3	11.046	6.077e-3
SCA in SR	2.275e-6	-6.077e-3	8.637	6.079e-3
SCA	0.000e-0	-6.077e-3	12.459	6.077e-3
SMA in SR	0.000e-0	-6.077e-3	6.338	6.077e-3
SMA	0.000e-0	-6.077e-3	11.195	6.077e-3
WOA in SR	0.000e-0	-6.077e-3	6.116	6.077e-3
WOA	0.000e-0	-6.077e-3	12.167	6.077e-3
Tie-line				
Method	OS	US	ST(<=0.005%)	PtP
MFO in SR	1.887e-4	-1.921e-4	42.073	3.808e-4
MFO	2.386e-4	-1.854e-4	38.139	4.239e-4
PSO in SR	2.925e-4	-1.718e-4	37.616	4.643e-4
PSO	2.837e-4	-1.641e-4	39.132	4.478e-4
SCA in SR	1.794e-4	-1.966e-4	42.023	3.760e-4
SCA	2.884e-4	-1.653e-4	39.775	4.537e-4
SMA in SR	2.486e-4	-1.821e-4	37.869	4.307e-4
SMA	2.493e-4	-1.722e-4	40.297	4.215e-4
WOA in SR	2.597e-4	-1.799e-4	37.503	4.396e-4
WOA	2.944e-4	-1.640e-4	39.345	4.584e-4

4.3. Robustness analysis

In this section, the robustness analysis of the LFC system against the parametric variations has been performed to analyze each model's sensitivity to parametric variation. It is accepted that only one of the system parameters changes at the rate of ±25% and ±50% at the same time. In addition to system parameter changes, variation of communication time delay as ±25% and ±50% have also been taken into account. It can be noted that crossing frequency is chosen as $w_c \ \epsilon$ [0–3.33] for robustness analysis. Thirty-two different stability region determined for variation of two-area system parameters and 8 different stability region are determined for communication time delays. The intersection of founded 40 stability regions is highlighted by red color as illustrated in Figure 10.

It can be clearly seen from this figure that variations of system parameters impact the stability region. Determined red colored region is important because it tolerates system parameter and time delay variations as ±25% and ±50%. That is, the results found with the heuristic algorithm applied in this region ensure that the system is robust against parameter changes. For this reason, the region determined by the red color is defined as the robust stability region.

In order to obtain system performance results for robust control analysis, WOA is chosen since it gives better results as shown in the previous section analysis. Obtained controller parameters, iteration number and computational time are given in Table 4.

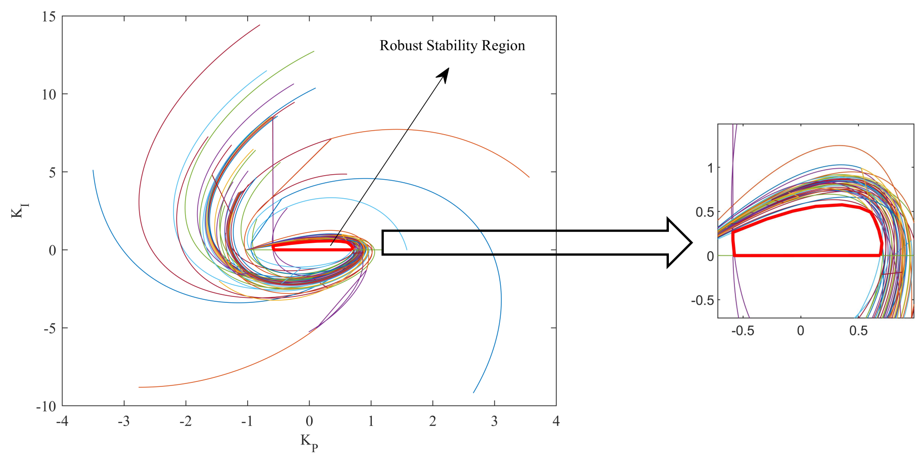

Figure 10. Stability regions according to variations of parameters (left), zoom of robust stability region (right).

Table 4. Controller parameters and performances of proposed method for robustness analysis.

Method	Ki	Kp	C. time	Iter.
WOA in SR	0.2651	0.1165	208.582	3

Frequency deviations of both regions and tie-line power deviation outputs for robust stability region are illustrated in Figure 11 and numerical performance results are given in Table 5.

Since the robust stability region is calculated by taking into account the system parameter changes (range between ±25% and ±50%), there is no need to consider system parameter changes in the analyses made within this region. Therefore, only one run of heuristic method is sufficient for robust control or sensitivity analysis.

5. Conclusion

It is very important to identify optimal control parameter gains that will provide optimum system performances quickly. In this study, two important contributions have been performed in order to realize the load frequency control of multiarea interconnected electrical power systems with communication time delay. Firstly, an objective function is developed to improve the frequency and tie-line power deviations of load frequency system. In this function, in addition to ITAE, time domain specifications (settling times and overshoots) of the system are also taken into account. Proposed function is compared with well-known integral error functions. Through

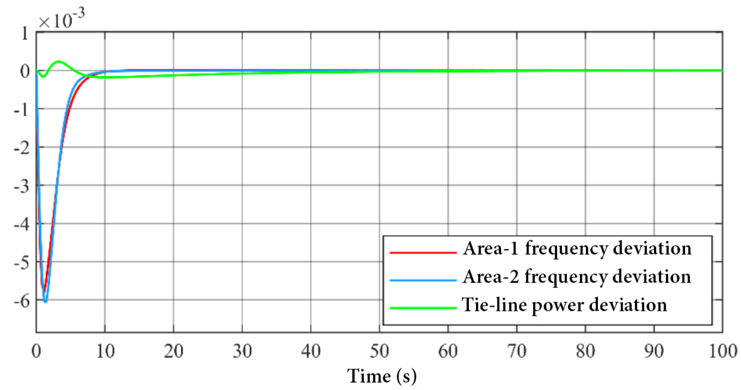

Figure 11. Areas frequency deviations and tie-line power deviation.

Table 5. Robust control analysis results via WOA.

Frequency deviation of area-1			
OS	US	ST(<=0.005%)	PtP
5.998e-6	-5.810e-3	9.634	5.816e-3
Frequency deviation of area-2			
OS	US	ST(<=0.005%)	PtP
0.000e-0	-6.065e-3	9.261	6.065e-3
Power deviation of tie-line			
OS	US	ST(<=0.005%)	PtP
2.311e-4	-1.801e-4	39.634	4.111e-4

this function, smooth and better performance outputs have been achieved and so outputs of the system are improved. Secondly, the stability regions for power system having CTD(s) have been found according to PI controller and the parameter selection has been carried out from this region. In this way, the stability of the system is guaranteed for all randomly assigned possible solutions by the heuristic algorithm. In addition, robust stability region for the two-area LFC is identified. The importance of this region is that effects of variations of system parameters are tolerated and so one run of the any heuristic method is enough to find optimal results. In order to demonstrate the validity and superiority of the proposed method, MFO, PSO, SCA, SMA, and WOA heuristic algorithms are used and the results are compared with both each other and classical approach. When analyzed obtained results, average computational time and average number of iterations are dramatically reduced 89.95% and 89.06%, respectively, via inserting of heuristics into the stability region method. In addition, steady state errors are minimized and transient state performances are improved.

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Appendix

System parameters definitions: β = frequency bias factor (pu MW/Hz); τ = communication time delay (s); D = damping constant (pu MW/Hz); M = inertia constant (pu MW s); R = speed regulation of governor (Hz/pu MW); T_g = governor time constant (s); T_{ch} = turbine time constant (s); T_{12} = synchronization constant (pu MW/rad).

System parameters: $\beta_1 = 21$, $\beta_2 = 21.5$; $\tau_1 = \tau_2 = 1.4142$; $D_1 = 1$, $D_2 = 1.5$; $M_1 = 10$, $M_2 = 12$; $R_1 = R_2 = 0.05$; $T_{g1} = 0.1$, $T_{g2} = 0.17$; $T_{ch1} = 0.3$, $T_{ch2} = 0.4$; $T_{12} = 0.0796$.