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Impact of Flexible AC Transmission System Devices on Automatic Generation Control with a Metaheuristic Based Fuzzy PID Controller

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Abstract: The present work proposes a teaching–learning-based optimization (TLBO)-tuned fuzzy proportional-integral-derivative (PID) controller of two-area hydro-thermal generating units for automatic generation control (AGC). The proposed system takes into account the physical constraints such as transport delay (TD), generation rate constraint (GRC), and governor dead band (GDB) nonlinearities. Firstly, fuzzy PID controllers were designed for both the areas and their gains were optimized using various minimization objective function criteria. Furthermore, applications of flexible alternating current transmission system (FACTS) devices such as static synchronous series compensator (SSSC), thyristor-controlled series capacitor (TCSC), thyristor-controlled phase shifter (TCPS), and unified power flow controller (UPFC) were investigated by integrating FACTS devices in appropriate locations of the system. The simulation results revealed that the minimum objective values were attained when the UPFC was placed in the system. Lastly, robustness analysis was done to observe the capability of the proposed controller with UPFC by changing system parameters and considering random load disturbances.

Keywords: automatic generation control (AGC); flexible alternating current transmission system (FACTS) device; fuzzy PID controller; random load disturbance; teaching–learning-based optimization (TLBO)

1. Introduction

In recent years, the consumption of power increased gradually regardless of power generation. This sudden increase in load creates some imbalances in power system operation such as the frequency and tie-line power deviations. This problem can be avoided by connecting a fast-acting automatic generation control for controlling the power generation between various control areas by holding the frequency as constant [1–4]. Automatic generation control plays a vital role in large-scale interconnected electrical power units to maintain the frequency and tie-line power as close as possible to the pre-defined values. The speed governing system in the AGC helps to manage the frequency and tie-line power within pre-defined values by varying the mechanical power input to the generators. A healthy power system must supervise the load changes and system disturbances to ensure an acceptable quality of power through the preservation of voltage and frequency within acceptable boundaries [5–8].

Several researchers focused on the significance of AGC and reported several soft computing techniques for obtaining optimal values of secondary controllers [9–16]. For example, Guha et al. [14] introduced a backtracking search evolutionary algorithm for the load frequency control (LFC) of power

systems. Fathy and Kassem [15] initiated an optimal LFC using a tuned adaptive neuro fuzzy inference system with an antlion optimizer. Pradhan and Bhende [16] proposed the online LFC of a power system based on a modification of the Jaya heuristic search algorithm. Khadanga and Kumar [17] executed a PID controller tuned by particle swarm optimization and a gravitational search algorithm for the LFC of a multi-source multi-area system. The performance of the high voltage AC or DC (HVAC/DC) link in the AGC was also presented, along with the ability of the static synchronous series compensator (SSSC) and capacitive energy storage (CES) devices. Guha et al. [18] initiated a differential search algorithm (DSA) for different power systems by considering a proportional-integral-derivative with filter (PIDF) controller, and they also showed its ability through a comparative analysis with other techniques. Chandrakala and Balamurugan [19] developed a combined system of an LFC and automatic voltage regulator (AVR) for a multi-source multi-area system tuned by simulated annealing. Ali and Abd-Elazim [20] proposed a bacterial foraging optimization algorithm to tune the parameters of a PID controller for a nonlinear LFC. Shabani et al. [21] proposed a resistant differential PID control technique tuned by an imperialist competitive algorithm for an LFC to eliminate the effect of disturbance.

In general, AGC is a slow control task; however, classical controllers like PID allow the system to react rapidly while varying its gain values, and its design is effortless. The proportional term helps the system to diminish the rise time, the integral term purges the steady-state error, and the derivative term improves the stability. The fuzzy PID controller has advantages over classical controllers, as its parameters can be tuned without having much knowledge on the system, and it exhibits simpler design properties than gain scheduling controllers [22–26]. In this paper, the teaching–learning-based optimization (TLBO) technique is proposed to produce optimal values, as it does not depend on any specific parameter [27]. Several researchers investigated flexible alternating current transmission system (FACTS) devices participating in power system applications for transient stability improvement [28–30]. For improving and speeding up performance in AGC, some FACTS devices are included in the power system model [31,32]. By taking all these issues into consideration, the present paper proposes controlling the AGC of a multi-area power system by using FACTS devices with the inclusion of non-linearities. The main objectives of the present work are as follows:

- i. To recommend a teaching–learning-based optimization (TLBO)-based fuzzy PID controller for the AGC problem;
- ii. To illustrate the superiority of the fuzzy PID controller with non-linearities such as the transport delay (TD), generation rate constraint (GRC), and governor dead band (GDB) for the AGC problem;
- iii. To demonstrate the performance of various FACTS devices incorporated in the system;
- iv. To observe the effectiveness of the fuzzy PID plus unified power flow controller (UPFC) device for various disturbances such as step and random step load disturbances.

The rest of the paper is organized as follows: Section 2 shows the methodology of the system model. Section 3 discusses the teaching–learning-based optimization algorithm. Simulation results, along with their analysis, are shown in Section 4. The concluding remarks about the designed controller are presented in Section 5.

2. Materials and Methods

In this paper, a two-area four-unit hydro and thermal system of equal 2000MW power capacity with 1640MW as nominal loading was examined. The analysis was made in a per unit system by considering 2000MW as a base value. The transfer function models of the thermal and hydro units were designed in MATLAB/SIMULINK (9.1.0.441655, R2016b version, Mathematical computing software, Natick, MA, USA) environment, and their related diagram is shown in Figure 1. The corresponding parameter values are specified in Appendix A. The considered power system shown in Figure 1 includes all the appropriate non-linearities such as GRC, GDB, and TD. The contribution of the different generating units contributing to the AGC problem are also represented by participation

factors. In present work, the hydro and thermal units contributed equally with a participation factor of 0.5. To have a realistic study, some non-linearities were considered. The thermal units in both areas were incorporated with a reheat turbine, a GDB of 0.05%, and a GRC of 3%. Similarly, hydro units were incorporated with a GDB of 0.02% and a GRC of 6%. A transport delay of 50 ms was also introduced for each generating unit, which considered the delay process of the system's components.

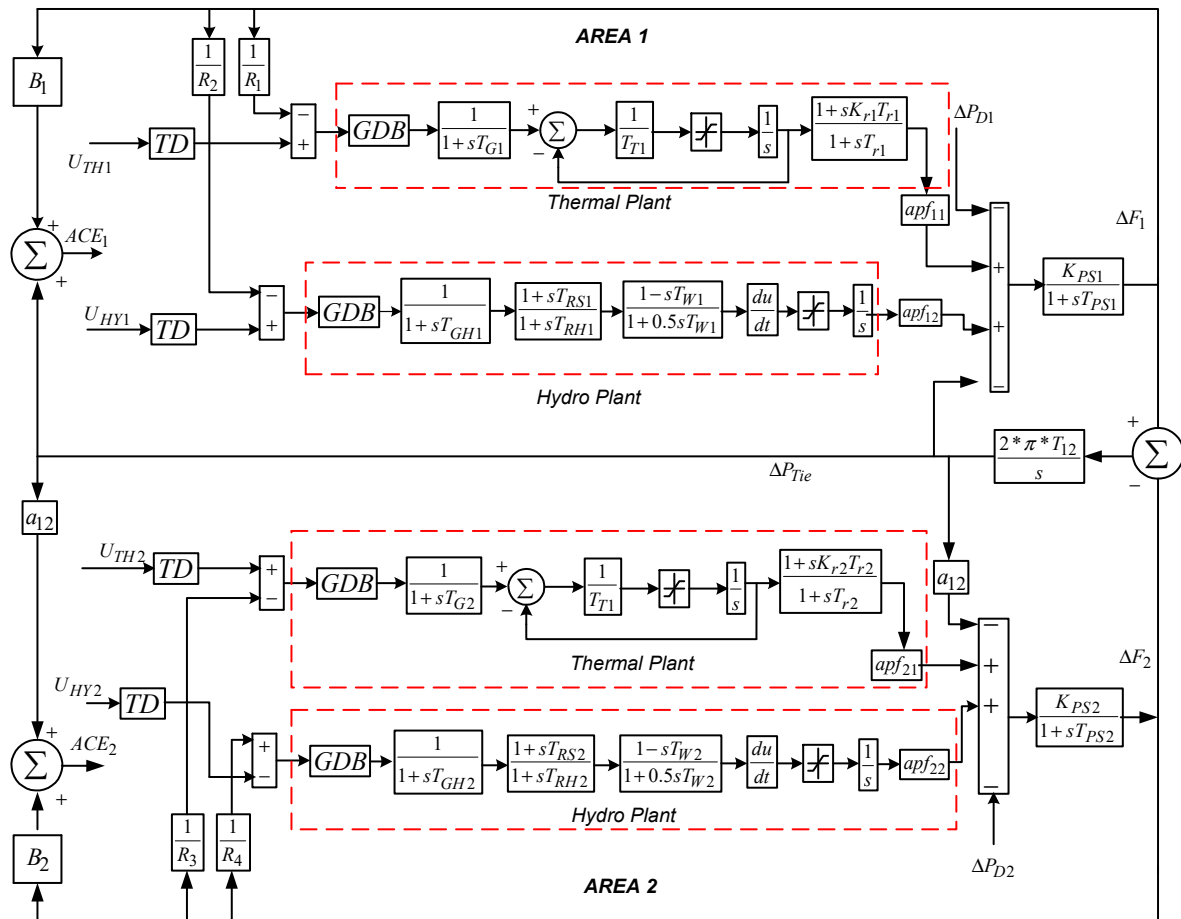


Figure 1. Two-area thermal and hydro power model.

Control Structure

Linear controllers such as integral (I), proportional-integral (PI), proportional-derivative (PD), and proportional-integral-derivative PID controllers were used to get the required transient and steady-state performance in various power electronics and power system applications to attain specified control objectives. However, linear controllers are not suitable for systems having higher order, with time delay and non-linearities. Fuzzy logic controllers (FLC) are non-linear controllers, which work well in closed-loop control systems; however, these controllers require fine-tuning in their design and implementation. Many researchers established that FLCs improve the closed-loop performance of classical controllers by updating the controller parameters online to handle the changes in the operating point [33–37]. However, the main limitation of the FLC is the lack of a systematic design process, and improper tuning of parameters may lead to the divergence of system stability. The tuning of FLC with rule-based membership functions (MFs) is complicated and, hence, may not be efficient. Gain tuning must be implemented, as it is the most familiar way of tuning the FLC to enhance the performance [33]. Therefore, rule-based standard MFs can be used for various applications, and scaling factors can be tuned for optimum fuzzy PID control [33]. Taking all these considerations into account, the fuzzy PID controller was chosen here to solve the AGC problem, as shown in Figure 2. The fuzzy controller

uses the error (e) and derivative of error ($\dot{e}$) as input signals. In the present study, the input signal was the area control error of the power system. Here, K_1 and K_2 were the input scaling factors of the FLC. The FLC output was multiplied with K_P , K_I , and K_D and then summed to give the total controller output. The outputs of the fuzzy controllers U_{THi} and U_{HYi} were the control inputs of the power system.

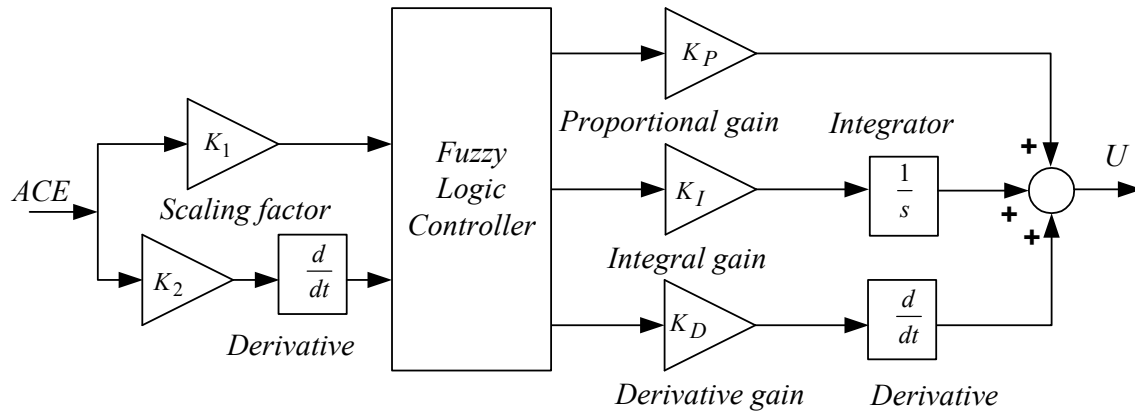


Figure 2. Structure of fuzzy PID controller.

The fuzziness of the FLC is characterized by MFs having different shapes such as triangular, bell, trapezoidal, sigmoid, gaussian, and piecewise linear. Out of these, bell, triangular, and trapezoidal MFs are preferred for real-time applications as they can be represented easily, need nominal memory storage, and can be manipulated efficiently through a fuzzy interface engine. From the literature, triangular MFs were extensively implemented in controller design, as the parametric practical depiction of these MFs is economical when compared to other MFs. Therefore, triangular MFs were considered in the present study. Moreover, an identical representation of MFs is preferred for having better computational effectiveness and superior memory usage [36]. Thus, similar MFs were selected for error, error derivative, and FLC output. The structure of the MFs (Mamdani type) is shown in Figure 3, which was considered for both the inputs and outputs.

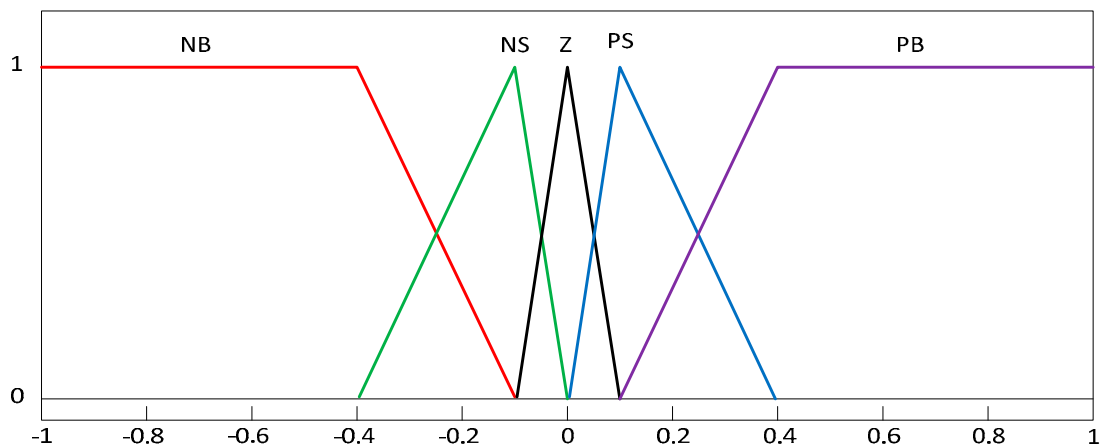


Figure 3. Schematic of membership functions (MFs) for inputs and outputs.

While evaluating the performance of any system through an optimization technique, an objective function must be defined based on the preferred constraints. Objective functions such as the integral of time-weighted absolute error (ITAE), integral of squared error (ISE), integral of time-weighted squared error (ITSE), and integral of absolute error (IAE) were used for the present study from the literature [21]. The ITAE criterion provides superior performance in terms of settling time and peak overshoot when

compared to IAE and ISE. Hence, ITAE was considered as the objective function in the present study, which allowed obtaining the optimal controller parameters of the fuzzy PID controller along with its scaling factors. However, the other objective functions IAE, ISE, and ITSE were also evaluated for the purpose of analysis. The expressions for the objective functions are provided in Equations (1)–(4).

$$J_1 = ISE = \int_0^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{Tie}|)^2 dt. \quad (1)$$

$$J_2 = IAE = \int_0^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{Tie}|) dt. \quad (2)$$

$$J_3 = ITSE = \int_0^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{Tie}|)^2 t dt. \quad (3)$$

$$J_4 = IAE = \int_0^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{Tie}|) t dt. \quad (4)$$

3. Teaching–Learning–Based Optimization (TLBO) Algorithm

The TLBO algorithm attracted the attention of several researchers, it was used for various engineering applications following its initiation in 2011 [27]. This algorithm does not utilize any detailed parameters like some other population-based or metaheuristics algorithms. It results in a constant convergence outcome and has the capacity to produce a high-convergence solution in a minimum time span. Mostly, the working principle of the TLBO algorithm depends on the student's nature and the influence of the training of the teacher in a classroom atmosphere. The teacher phase and learner phase are the two major phases of TLBO, where students (learners) acquire knowledge from the teacher in the teacher phase, while students acquire knowledge through interaction between learners (students) in the learner phase. The flowchart of the TLBO algorithm is shown in Figure 4. The various actions concerned in the TLBO algorithm are described as below [27].

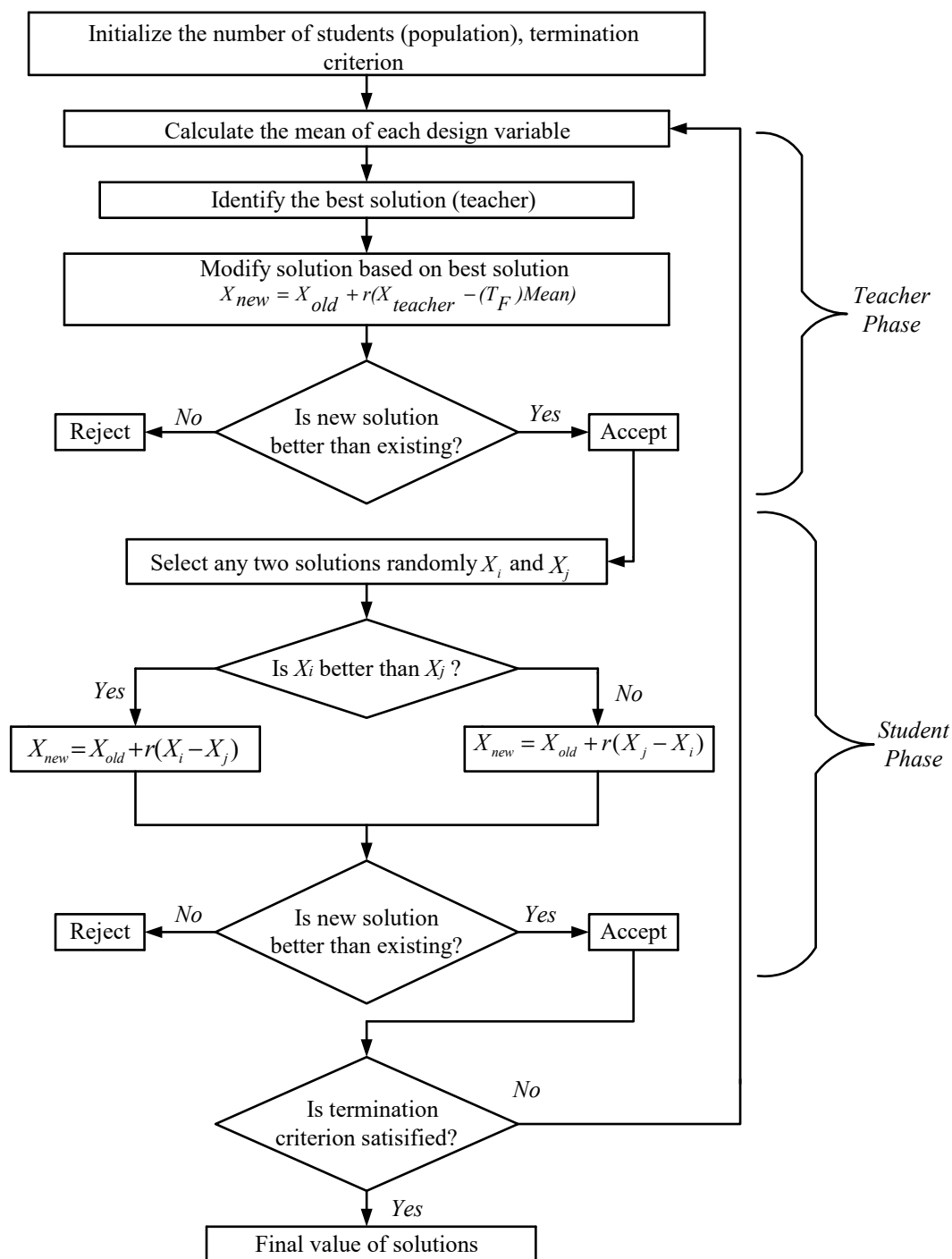


Figure 4. Flowchart of teaching–learning-based optimization (TLBO) technique.

3.1. Initialization

In this phase, the initial population of range $NP \times D$ is arbitrarily produced, where NP is the size of the population (number of learners), and D is the dimension of the problem (number of offered subjects). The i th column of the initial population signifies the marks secured by different learners in the i th subject.

The initial population is given as follows:

$$X = \begin{bmatrix} x_{1,1} & x_{1,2} & \dots & x_{1,D} \\ x_{2,1} & x_{2,2} & \dots & x_{2,D} \\ \vdots & \vdots & \dots & \vdots \\ x_{NP,1} & x_{NP,2} & \dots & x_{NP,D} \end{bmatrix}. \quad (5)$$

3.2. Teacher Phase

In this phase, every teacher evaluates the mean outcome of a class in the study allocated to them. The teacher instructs the supposedly apt learners, whereby the best solution is recognized and allocated by the teacher. Marks acquired by various students for each subject can be calculated as follows:

$$M_d = [m_1, m_2, \dots, m_D]. \quad (6)$$

The variation among the mean outcome in a specific subject and the result of the corresponding teacher are given by

$$M_{diff} = rand(0, 1)[X_{best} - T_F M_d], \quad (7)$$

where $rand(0, 1)$ is a random number between 0 and 1, and T_F is the teaching feature; its value is considered as either 1 or 2 and determined randomly using Equation (8).

$$T_F = round[1 + rand(0, 1)]. \quad (8)$$

The active population is simplified using Equation (9).

$$X_{new} = X + M_{diff}. \quad (9)$$

If $f(X_{new}) < f(X)$, then elements of X_{new} are accepted.

3.3. Learner Phase

In this phase, a learner chooses another learner randomly and aims to enhance their intelligence through communication. A learner develops their ability via communication if the other learner has more knowledge than them. The process of learning can be described as follows:

Select two learners X_i and X_j randomly such that $i \neq j$ as follows:

$$X_{new} = X_i + rand(0, 1)(X_i - X_j), \text{ if } f(X_i) < f(X_j), \quad (10)$$

else

$$X_{new} = X_j + rand(0, 1)(X_j - X_i) \quad (11)$$

Admit X_{new} if it produces a better result.

4. Results and Discussion

Originally, a dual-field hydro-thermal power scheme was studied and discussed in Section 2. A step load perturbation (SLP) of 1% was applied in area1 and fuzzy PID controllers were incorporated to minimize the frequency and tie-line power deviations. The optimal values of fuzzy PID controller parameters were obtained using the TLBO technique and the optimal values were finalized by employing various objective functions mentioned in Section 2. The performance index values obtained for the fuzzy PID controller were as follows: ISE = 0.0030; ITSE = 0.0060; IAE = 0.1901; ITAE = 0.8506. To improve the dynamic responses, different FACTS devices such as static synchronous series compensator (SSSC), thyristor-controlled series capacitor (TCSC), thyristor-controlled phase shifter (TCPS), and unified power

flow controller (UPFC) were incorporated in the tie-line. The considered FACTS devices were connected in the tie-line to improve voltage stability and transient stability, as well as offer better power oscillation damping. For a better understanding, the single line diagram of the proposed power system with the UPFC device is shown in Figure 5. The parameters of the fuzzy PID controller for various cases are provided in Table 1, and the performance index values are tabulated in Table 2; Table 3. From Tables 2 and 3, it is shown that the performance index values were reduced upon incorporating FACTS devices. For the same system, smaller objective function values were obtained with the fuzzy PID with UPFC ($ISE = 9.0459 \times 10^{-5}$; $ITSE = 1.0963 \times 10^{-4}$; $IAE = 0.0377$; $ITAE = 0.5600$) when compared to the SSSC ($ISE = 0.0011$; $ITSE = 0.0025$; $IAE = 0.1297$; $ITAE = 0.7814$), TCPS ($ISE = 0.0018$; $ITSE = 0.0037$; $IAE = 0.1500$; $ITAE = 0.7040$), and TCSC ($ISE = 0.0018$; $ITSE = 0.0024$; $IAE = 0.1266$; $ITAE = 0.6194$). Table 3 also reveals that the values of settling time and under shoots were lower for the UPFC-incorporated system when compared to others.

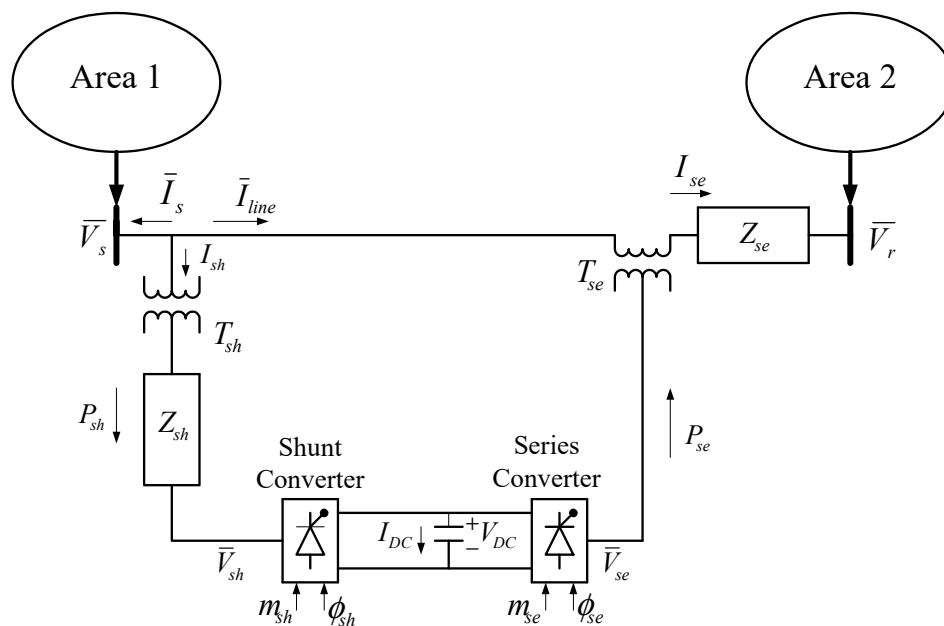


Figure 5. Single line diagram of two-area power system with unified power flow controller (UPFC).

Table 1. Parameters of Fuzzy PID controller. SSSC—static synchronous series compensator; TCSC—thyristor-controlled series capacitor; TCPS—thyristor-controlled phase shifter (TCPS); UPFC—unified power flow controller.

Controller/Parameters	Fuzzy PID	Fuzzy PID-SSSC	Fuzzy PID-TCPS	Fuzzy PID-TCSC	Fuzzy PID-UPFC
K_1	0.3069	0.3346	1.3115	1.3514	0.4029
K_2	0.7468	0.0995	0.8310	1.1099	0.1349
K_{P1}	1.2990	1.9143	0.4037	0.8476	1.4560
K_{I1}	0.8412	0.2396	0.2330	0.1426	1.2428
K_{D1}	1.1929	1.5844	0.4103	0.2324	0.2516
K_3	1.7536	0.5365	1.2096	0.7176	0.0003
K_4	0.8823	0.1064	0.2825	0.0254	1.2729
K_{P2}	0.6942	0.0756	1.8789	0.8073	0.4309
K_{I2}	0.4353	1.9600	0.5387	0.0420	0.6168
K_{D2}	0.0757	1.0155	0.3075	0.5739	0.0619

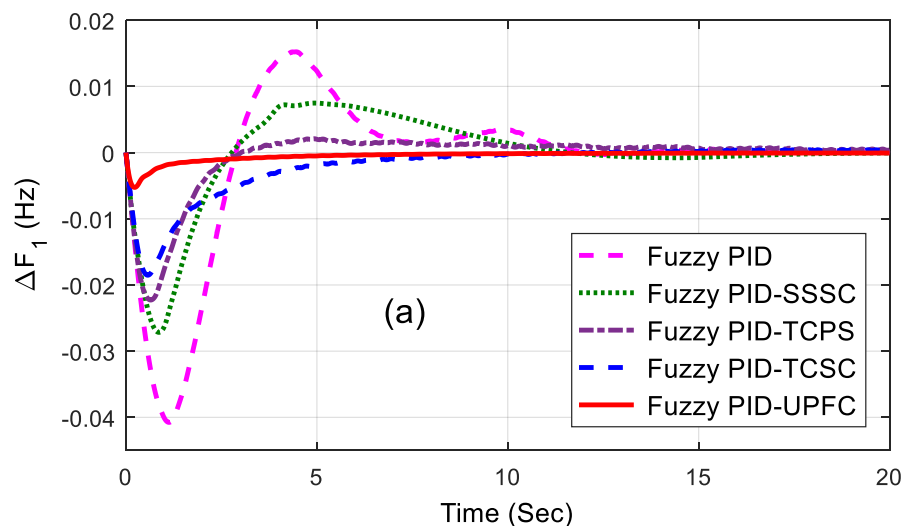
Table 2. Index values.

Type of Controller	T_s (Sec)			U_s (–ve) (Hz)		U_s (–ve) (puMW)
	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}
Fuzzy PID	19.71	18.36	16.88	0.0408	0.014	0.0036
Fuzzy PID-SSSC	17.87	18.10	16.88	0.0271	0.006	0.0002
Fuzzy PID-TCPS	17.07	22.35	4.76	0.0222	0.015	0.0035
Fuzzy PID-TCSC	15.69	21.65	4.52	0.0077	0.037	0.0765
Fuzzy PID-UPFC	8.84	17.35	4.28	0.0053	0.007	0.0052

Table 3. Function values. ITAE—integral of time-weighted absolute error (ITAE); ISE—integral of squared error; ITSE—integral of time-weighted squared error; IAE—integral of absolute error.

Type of Controllers	Objective Functions (J_s)			
	$J_1 = \text{ISE}$	$J_2 = \text{IAE}$	$J_3 = \text{ITSE}$	$J_4 = \text{ITAE}$
Fuzzy PID	0.0030	0.1901	0.0060	0.8506
Fuzzy PID-SSSC	0.0011	0.1297	0.0025	0.7814
Fuzzy PID-TCPS	0.0018	0.1500	0.0037	0.7040
Fuzzy PID-TCSC	0.0018	0.1266	0.0024	0.6194
Fuzzy PID-UPFC	9.0459×10^{-5}	0.0377	1.0963×10^{-4}	0.5600

The related dynamic performances of the system are shown in Figure 6a–c, where it can be noted that the system with the UPFC provided the best performance compared to others. The dynamic performance of the system was assessed for 1% SLP in area2 without retuning the control parameters, and the equivalent responses are shown in Figure 7a–c. The superiority of the system incorporated with a fuzzy PID and UPFC was also shown by evaluating the eigen values of the proposed system, as tabulated in Table 4. From the concept of relative stability, it is known that the system is better damped if it has more negative eigen values or if the poles of the congested loop scheme are further away from the imaginary axis. From Table 4, it can be noted that the eigen values of the UPFC structure were more adverse than the others and, therefore, it provided better damping.

**Figure 6.** Cont.

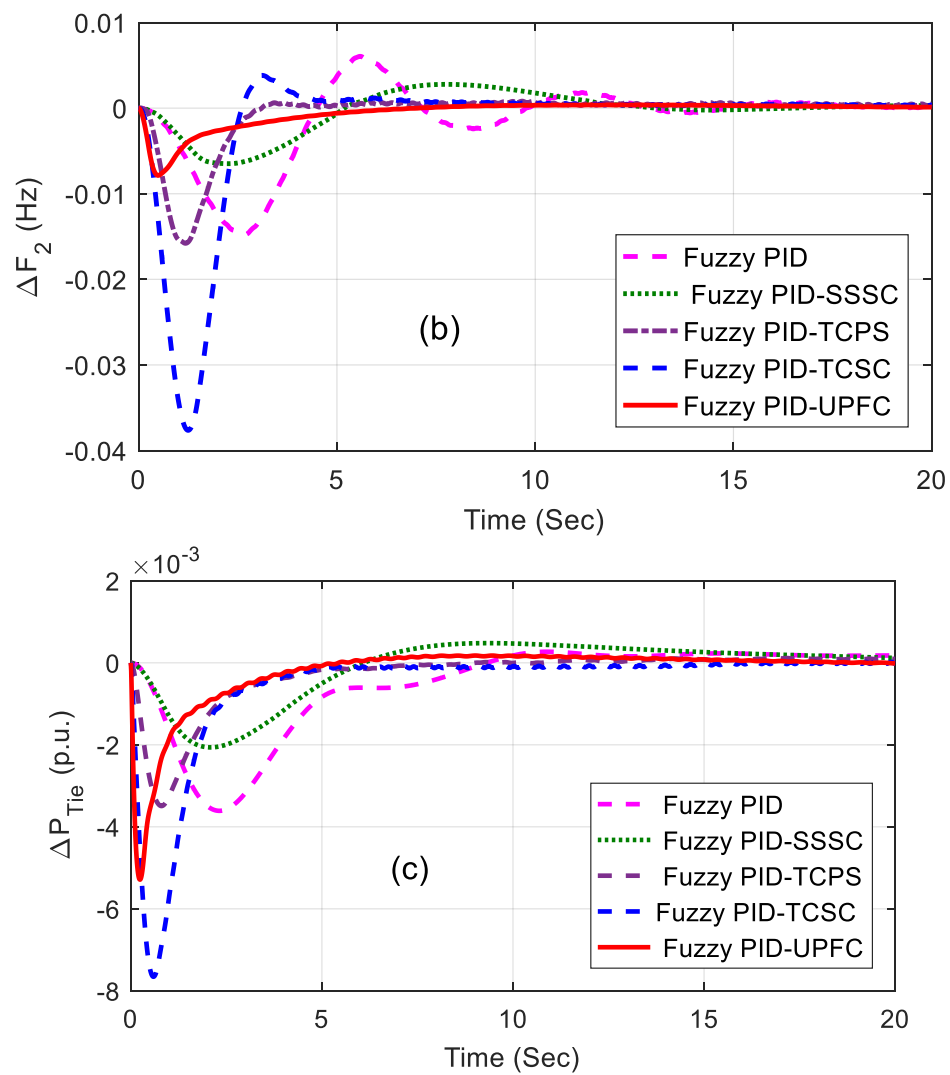


Figure 6. (a–c) Dynamic performance of 1% step load perturbation (SLP) in area1.

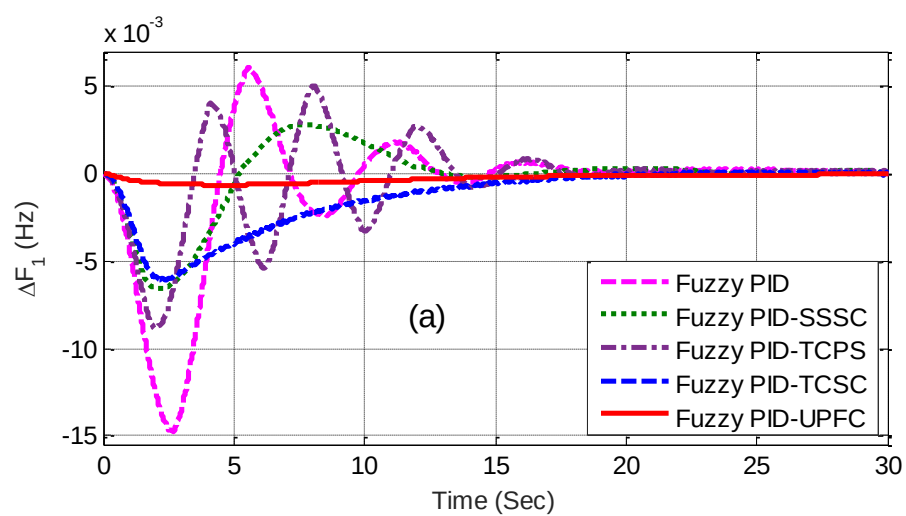


Figure 7. Cont.

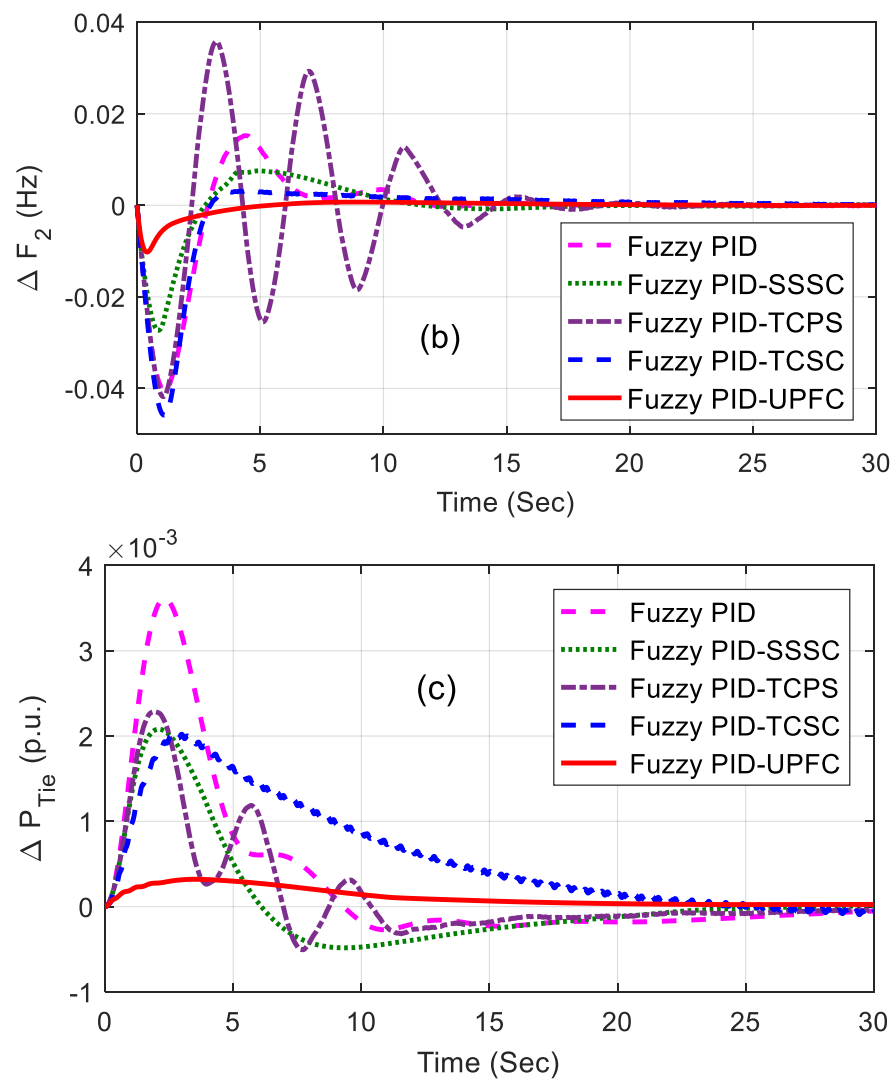


Figure 7. (a–c) Dynamic performance of 1% SLP in area2.

Table 4. Eigen values of the proposed system.

Fuzzy PID	Fuzzy PID-SSSC	Fuzzy PID-TCPS	Fuzzy PID-TCSC	Fuzzy PID-UPFC
$-0.0250 + 0.9207i$	-33.3056	-9.1524	-47.4704	-93.2746
$-0.0250 - 0.9207i$	-5.015	$-0.4488 + 0.8518i$	-2.1673	-10.7105
$-0.0500 + 0.0000i$	-4.408	$-0.4488 - 0.8518i$	-0.4123	-4.07
-2	$-0.0280 + 0.9190i$	-0.0500	-0.05	-0.0849
-1.9493	$-0.0280 - 0.9190i$	-2	-2	-2
-0.0205	-0.1001	-1.9493	-1.9493	-1.9493
-2	-0.05	-0.0205	-0.0205	-0.0205
-1.9493	-2	-2	-2	-2
-0.0205	-1.9493	-1.9493	-1.9493	-1.9493
-0.1	-0.0205	-0.0205	-0.0205	-0.0205
-3.3333	-2	-0.1	-0.1	-0.1
-12.5	-1.9493	-3.3333	-3.3333	-3.3333
-0.1	-0.0205	-12.5	-12.5	-12.5
-3.3333	-0.1	-0.1	-0.1	-0.1
-12.5	-3.3333	-3.3333	-3.3333	-3.3333
	-12.5	-12.5	-12.5	-12.5
	-0.1			
	-3.3333			
	-12.5			

Robustness Analysis

Robustness analysis was performed to realize the capacity of the controller for broad changes in the system's parameters and operating conditions. This analysis was performed for the fuzzy PID controller with the UPFC-incorporated system as it performed better than the other systems. The system parameters and loading conditions were varied in the range of -25% to $+25\%$ without re-optimizing values of the fuzzy PID controller. The system performance index values such as the objective functions and settling times for 1% disturbance in area1 are provided in Table 5. From Table 5, it can be noted that the performance index values obtained under various conditions were more or less equal to the nominal values and, hence, the proposed controller can be considered a robust controller. The corresponding responses under various conditions are shown in Figures 8a–c and 9a–c. From these figures, it can be pointed out that the responses of the system were sensitive to the variation in load and system parameters.

Furthermore, the effectiveness of the proposed controller was also analyzed by introducing a random step load as shown in Figure 10, and it was tested for the fuzzy PID controller with TCSC- and UPFC-incorporated systems, which showed superior performance. The step load disturbance was varied randomly from 0 s to 150 s, and the responses of the system were observed. In general, the frequency decreased when the load increased and viceversa. The best scenario considered the random load from 10 s to 20 s, as it increased when the system's frequency decreased accordingly. The related responses in Figure 11a–c show how the system responded to a random step load. From these responses, it can be commented that the proposed controller can withstand any sudden changes in load disturbance.

Table 5. Performance index values under system parameter variation.

Variation of Parameter	% Change	Settling Time Ts (s)			Obj
		ΔF_1	ΔF_2	ΔP_{Tie}	ITAE
Nominal	0	8.84	17.35	4.28	0.2433
Loading condition	+25	8.84	17.34	4.28	0.2433
	−25	8.83	17.34	4.28	0.2434
T_g	+25	9.05	17.50	4.25	0.2465
	−25	8.47	17.50	4.25	0.2391
T_t	+25	8.23	16.24	4.11	0.2327
	−25	9.52	18.94	8.01	0.3089
T_{12}	+25	9.31	16.90	4.03	0.2394
	−25	7.90	17.96	4.34	0.2445

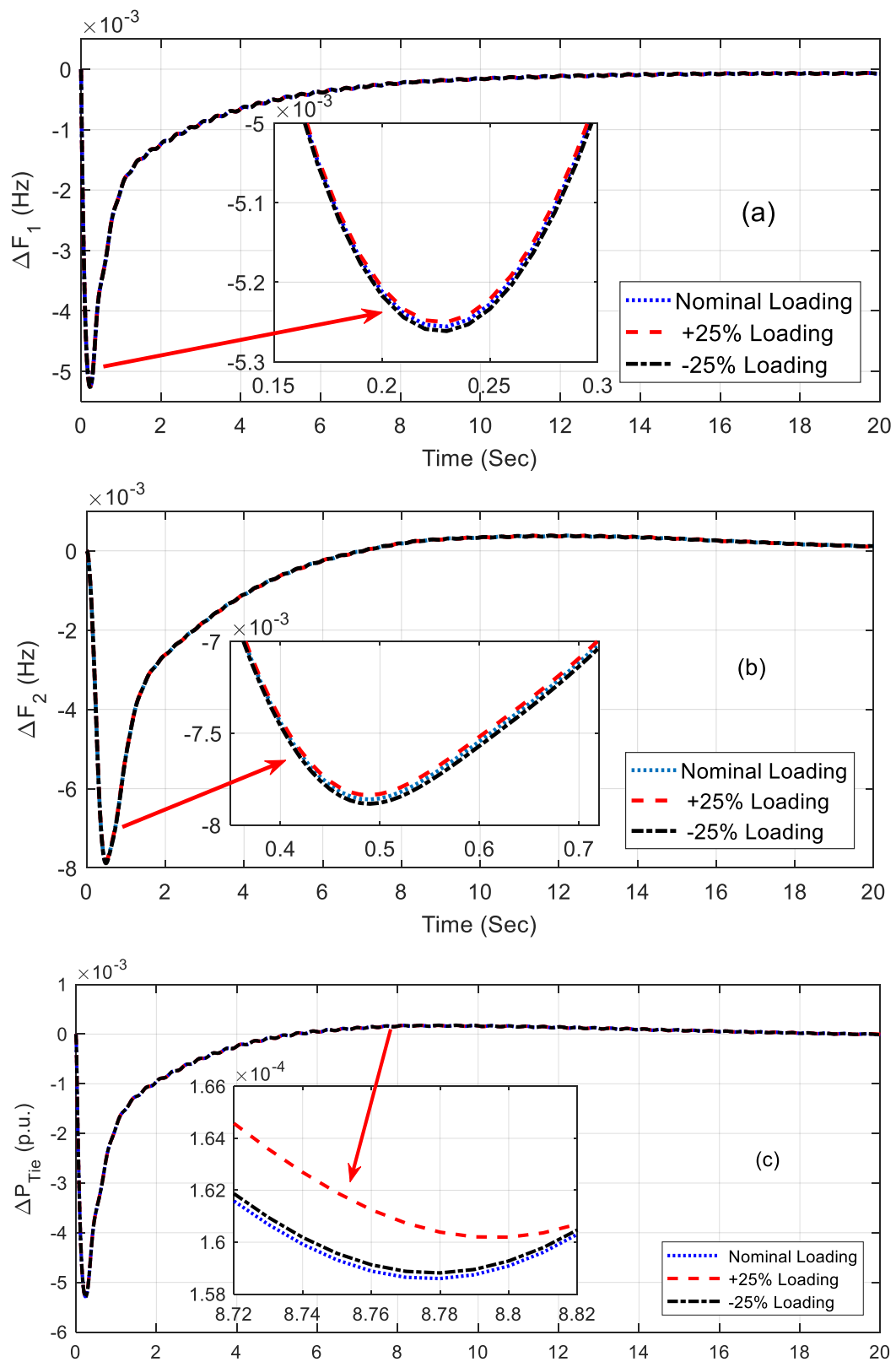
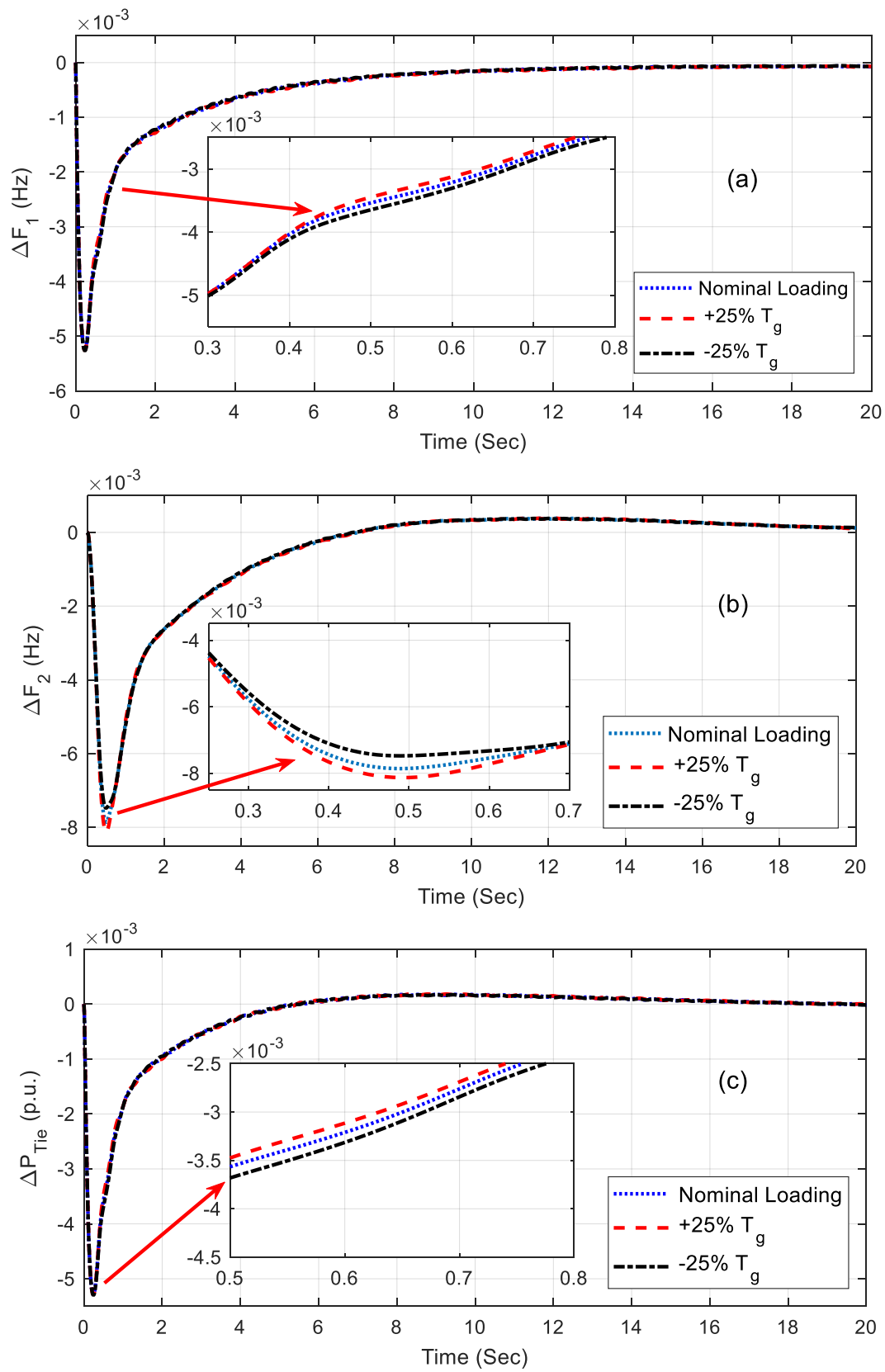


Figure 8. (a–c) Responses under loading variation.

Figure 9. (a–c) Responses under T_g variation.

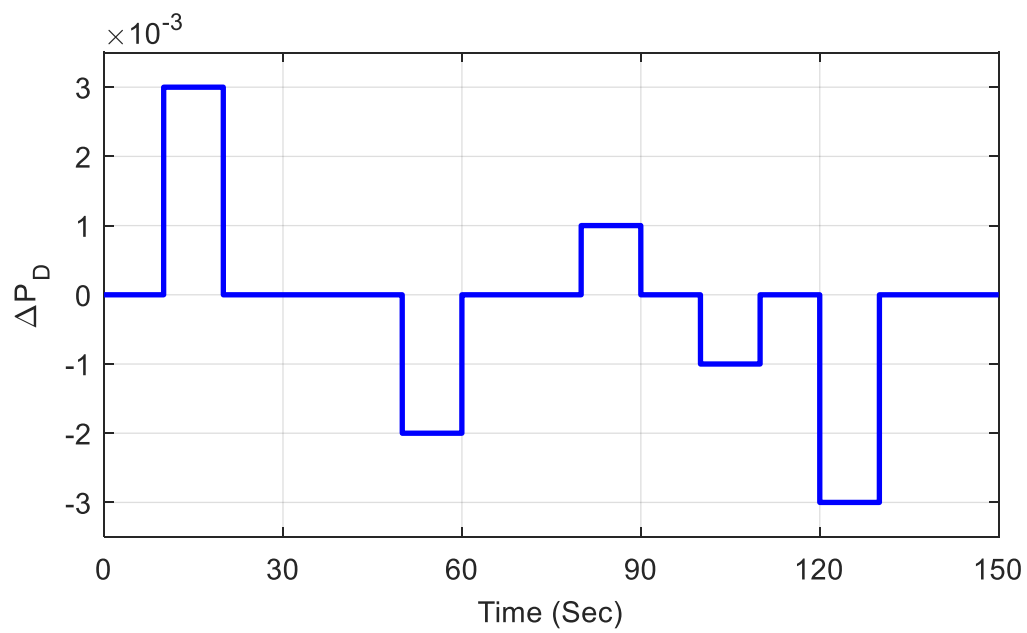


Figure 10. Random step load variation.

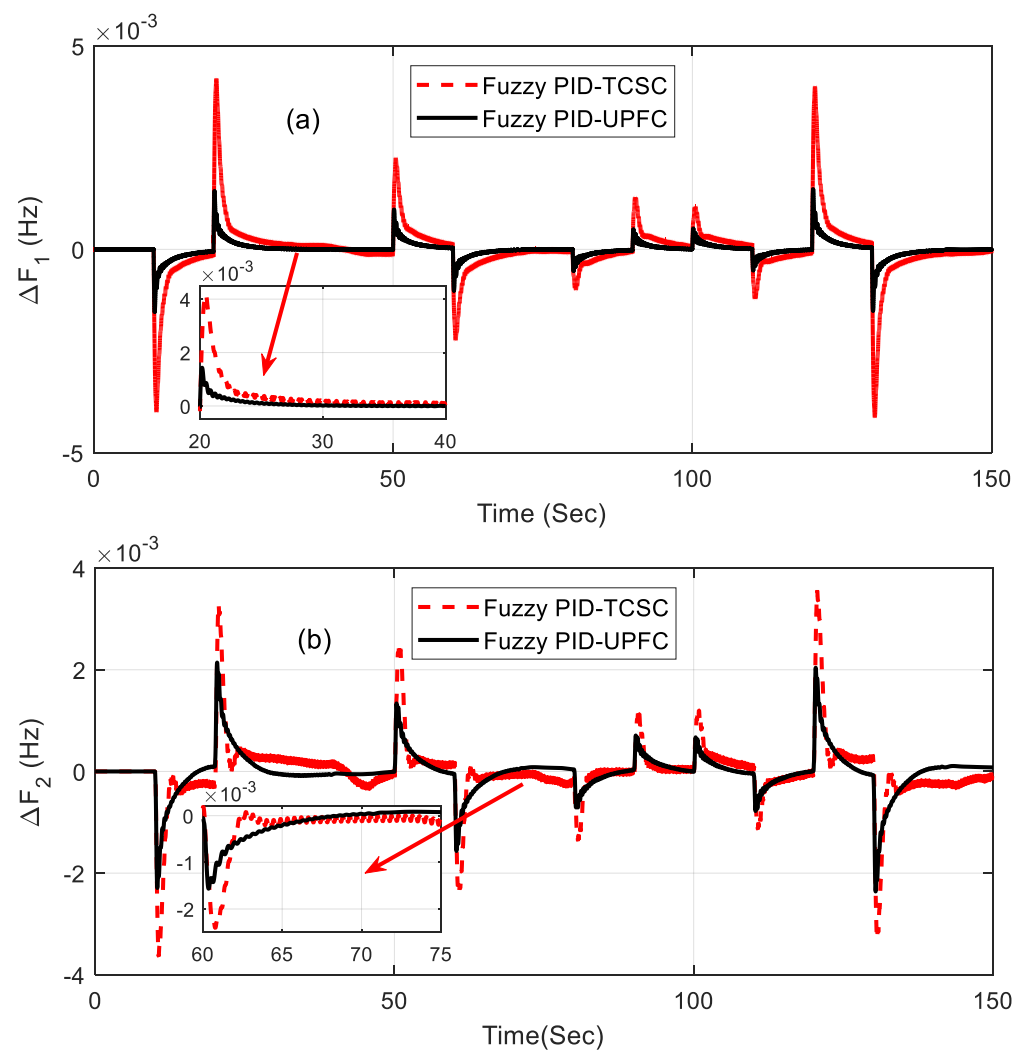


Figure 11. Cont.

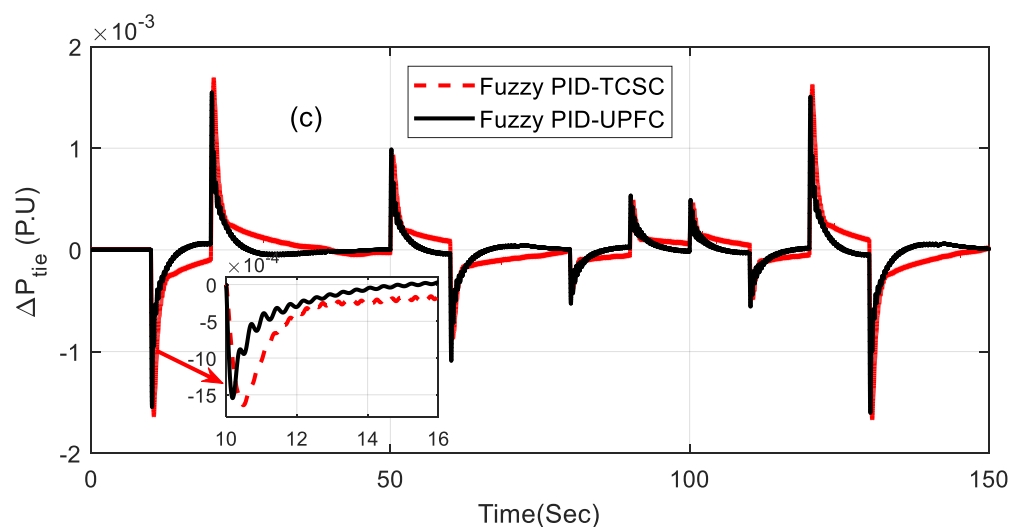


Figure 11. (a–c) Responses under step load variation.

5. Conclusions

An impact of FACTS devices was observed for the AGC problem of a two-area hydro-thermal power system. Non-linearities such as TD, GRC, and GRB for the two hydro and thermal units were included in the system for realistic analysis. A fuzzy PID controller was used as a secondary controller where the scaling factors and gain values were obtained using the TLBO technique. After testing the designed system with a fuzzy PID controller, FACTS devices such as SSSC, TCPS, TCSC, and UPFC were included in the tie-line to improve the results, and they were compared. The simulation results showed that the fuzzy PID plus UPFC-integrated system performed better than the others. The capability of the fuzzy PID plus UPFC was also investigated for variations in system parameters and random step load disturbances. Future work will focus on testing other metaheuristic optimization techniques for the proposed system. In addition, designing a type-2 fuzzy logic controller for the proposed system tuned with different bio-inspired metaheuristic techniques is another line of our future research.

In this paper, we tried to prove the fuzzy PID controller's superiority over the traditional PID controller. As it is a new approach, its application was restricted to a two-area power system of equal area with two different units in each area interlinked by a tie-line. We tested its robustness and capability to handle non-linearities like transport delay (TD), generation rate control (GRC), and governor dead band (GDB) introduced in the system. The above approach can be extended to a multi-area power system with multiple sources in each area and it can also be tested with renewable energy sources in the system for the AGC problem. Although the fuzzy PID controller proved to be a better controller than traditional controllers with an increase in non-linearities in the system, it became a tedious process to simulate in the MATLAB/SIMULINK (9.1.0.441655, R2016b version, Mathematical computing software, Natick, Massachusetts, USA) environment. The time taken by the fuzzy PID system for each iteration is greater compared to the conventional PID system. Therefore, in the future, the aim will be to improve the time taken for each iteration. It is expected that fractional controller performance can be achieved by the proper tuning of controller parameters. In this regard, work can be planned on the application of evolutionary optimization techniques for the optimal configuration of fractional controllers.

Author Contributions: Ramana Pilla and Tulasichandra Sekhar Gorripotu proposed main idea of the paper and analyzed in MATLAB/SIMULINK environment. Ahmad Taher Azar has developed fuzzy system and extensively reviewed the manuscript. All authors read and approved the final manuscript.

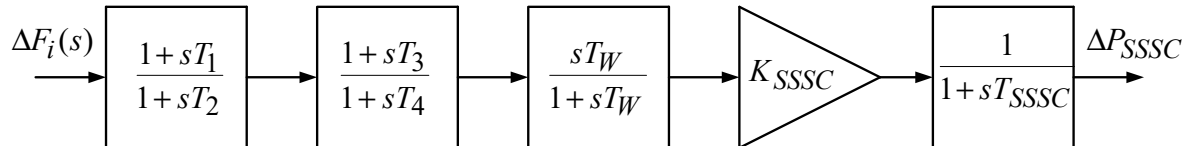
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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

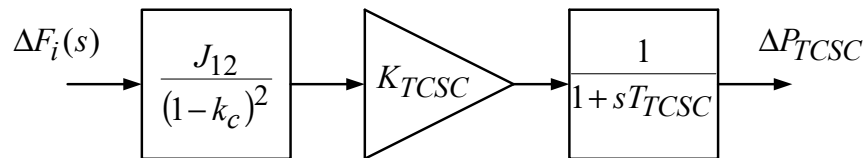
Nomenclature	Value
i	Subscript referred to area i (1, 2)
F	Nominal system frequency (Hz)
P_{Ri}	Rated power of area i (MW)
ΔF_i	Incremental change in frequency of area i (Hz)
ΔP_{Di}	Incremental step load change of area i
ΔP_{Tie}	Incremental change in tie-line power between areas 1 and 2 (p.u.)
ACE_i	Area control error of area i
B_i	Frequency bias parameter of area i (p.u. MW/Hz)
T_{Gi}	Speed governor time constant for thermal unit of area i (s)
T_{Ti}	Steam turbine time constant of area i (s)
T_{PSi}	Power system time constant of area i (s)
K_{PSi}	Power system gain of area i (Hz/p.u. MW)
T_{12}	Synchronizing coefficient between areas 1 and 2 (p.u.)
K_{ri}	Steam turbine reheat constant of area i
R	Regulation parameter
T_{ri}	Steam turbine reheat time constant of area i (s)
T_{Wi}	Nominal starting time of water in penstock of area i (s)
T_{RSi}	Hydro turbine speed governor reset time of area i (s)
T_{RHi}	Hydro turbine speed governor transient droop time constant of area i (s)
T_{GHi}	Hydro turbine speed governor main servo time constant of area i (s)
T_F	Teaching feature
t_{sim}	Simulation time (s)
a_{12}	$-P_{R1}/P_{R2}$
apf	Area participation factor

Appendix A.1 Transfer Function Model and Data for SSSC



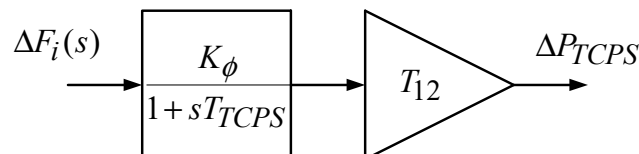
$K_{SSSC} = 0.001$; $T_{SSSC} = 0.03$ s; $T_1 = 0.2651$ s; $T_2 = 0.2011$ s; $T_3 = 0.6851$ s; $T_4 = 0.2258$ s; $T_W = 10$ s.

Appendix A.2 Transfer Function Model and Data for TCSC



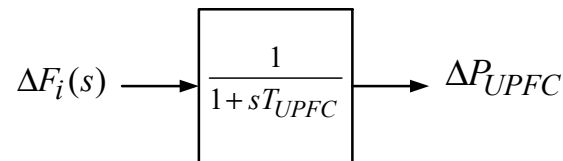
$K_{TCSC} = 2$; $T_{TCSC} = 0.02$ s; $J_{12} = 0.05$; $k_c = 0.5$.

Appendix A.3 Transfer Function Model and Data for TCPS



$$K_{\varphi} = 1.5; T_{TCPS} = 0.1 \text{ s.}$$

Appendix A.4 Transfer Function Model and Data for UPFC



$$T_{UPFC} = 0.01 \text{ s.}$$

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