The Application of Optimum Self-Tuning Fuzzy Logic Controllers in Multi-Area Power Systems Including UPFC

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***Abstract*—In this paper, self-tuning fuzzy logic controllers have been designed for load frequency control of power systems using the integral of time-absolute error (ITAE) and integral of time multiply squared error (ITSE) as optimization criteria and the maximum of area control error (ACE) as error signal. The optimal control parameters are obtained using the teaching–learning-based optimization algorithm which has a high accuracy and a high convergence speed. All simulations and coding were done MATLAB software in order to optimize the design of the controller. The effectiveness of the proposed method was shown on a two-area three-power plant power system under area load disturbances. After evaluating and comparing the performance of the optimized controller with the non-optimized controller, it was concluded that the optimized self-tuning fuzzy logic controller (OSTFLC) has a better and more robust performance than a STFLC in a wide range of electrical load variations occurred in both areas. To reach the above mentioned goal, optimization of the membership function, error and it's derivative are done simultaneously. At the, same time the fuzzy PID controller and UPFC system parameters are also optimized, through the use of TLBO algorithm. An optimal control system and an optimal modelling of the system are the main contributions of this paper.**

Keywords*—Teaching–learning-based optimization (TLBO) algorithm, Self-tuning fuzzy logic controller (STFLC), Load frequency control (LFC), Two-area three-machine power system, Unified Power Flow Controller (UPFC)

I. Introduction

In large-scale power systems which usually consist of an interconnected control area, load frequency control is very important in keeping the power system frequency within the area close to planned values. Mechanical power input to the generator is applied for the frequency control of the electrical power output and for preserving the power exchange between areas according to the plan. In a deregulated power system, each control area has various uncertainties and disturbances as a result of the increased complexity, system modeling errors, and restructuring the power system [1,2]. In recent decades, researchers have proposed several strategies for LFC in power systems. Among intelligent on-line controllers, fuzzy logic controller has attracted much attention. This is because it does not need a mathematical model of the controlled system. If the system under control is a nonlinear and complex one, LFC will be difficult to be modeled, thus a FLC can be very effective for it [2,3]. The advantages of FLC compared to a conventional controller are as follows: they are cheap, cover a wide range of operating conditions and are flexible according to natural language terms. In addition, FLCs have self-tuning, nonlinear matching, and time-varying features. In [3] a definition and development of an optimal hierarchical demand-side power-system primary-frequency control structure has been given to prepare a trustworthy complement the inertia of generator and governor answer, in the middle of the interarea oscillation damping. In [4] three main controllers including Fuzzy, Anfis as well as PID controllers have been given in order to stabilize the frequency of a micro grid while it has been isolated from utility. In [5] two algorithms such as cuckoo optimization algorithm and harmony search algorithm have been emerged in order to enhance Fuzzy-PID controller's response for solving the LFC problem of power system. In [6] a fractional order proportional-integral-derivative (FOPID) controller has been introduced for parallel control structure power system in order to stabilize the frequency changes. In [7] a tuned PID controller with PSO algorithm has been used in the real power network in the Egypt. The power system includes conventional generators and wind farm. In [8] an improved version of gray wolf optimizer algorithm has been used to tune Fuzzy-PID controller to reduce frequency division in power system. In [9] the response of Fuzzy-PID/PI controllers have been improved by proposed hybrid algorithm (pattern search and deferential eveloution). In [10] a new combination of Local Unimodal Sampling (LUS) and TLBO algorithm founded on fuzzy-PID controller has been used for solving LFC problem. In [11], the PID controller has been tuned by Elephant Herding Optimization algorithm for LFC problem. In FLCs, these nonlinear properties are considered by a limited number of if-then rules which may not always be enough for a suitable control signal. To overcome these limitations, many research have been done on the settings of FLCs [12-16]. One way to solve this problem is to use adaptive scaling coefficients [15-16]. The results demonstrate that this solution can improve the performance of FLC. In [17] the use of a set of coefficients of switchable scaling has been proposed, but the best performance was achieved only in simple first-order systems. Another problem of FLC is how to set the parameters of this controller. To solve this problem the steady state of system is usually formulated in the form of an optimization problem and solved using optimization algorithms [14]. These methods, including the use of off-line methods combined with on-line methods for designing controllers are referred to as ‘intelligent combined methods’ [18]. The main contributions of this paper can be divided into two parts: innovation in control system and innovation in the modelling of the system. The system is controlled by a Fuzzy-PID controller optimized by TLBO. In this control system, PID controller parameters are set by the Fuzzy system and are optimized by TLBO algorithm. In previous papers, only the PID parameters were optimized by heuristic algorithms while in this paper in addition to PID parameters, input and output coefficients and membership functions of fuzzy system are simultaneously optimized. Another innovation that has been used in the system model is the modeling of a two-area multi-machine power system in the presence of UPFC. In this study, the coefficients of UPFC are optimized simultaneously with inputs and outputs and membership functions of the fuzzy controller system. In this research, an intelligent method including a self-tuning fuzzy structure combined with a TLBO algorithm has been proposed to overcome the above-mentioned problems. The system under study is a two-area three-machine power system including thermal, gas, and hydroelectric power plants.

II. The System Under study

A. System Model

The linear model of a single-machine infinite-bus (SMIB) power system is shown in Fig. 1-a. The block transform functions of this power system are as follows [19-20]:

$\frac{1}{1+T_T S}$ Steam turbine

$\frac{1}{2HS+D}$ Load & machine

$\frac{1}{R}$ droop characteristic of the governor

In order to keep the system frequency constant at the nominal value, a supplement control action such as a controller in the form of KI/s is usually required. In the power system frequency control, this controller is also designed in the form of a PID controller. The controllers for a single machine system and a multi-machine system, are shown in Figs. 1-a and 1-b, respectively. The data of the two-area three-machine power system are available in the appendix.

B. Unified Power Flow Controller (UPFC)

Nowadays, with the development of power electronics, using the flexible AC transmission system (FACTS) devices to enhance control performance and increase the transmission lines capacity has been taken into more concentration. FACTS devices, by changing transmission lines characteristic parameters such as series and shunt impedance, change the phase angle. The phase angle is the main barrier to line capacity increase, so FACTS devices, by changing the phase angle, guarantee the safety and flexibility of transmission line’s dynamic stability. UPFC is one of the most efficient types of FACTS devices. In UPFC the series and shunt impedances work individually and simultaneously, UPFC is a combination of static compensator (STATCOM) and static synchronous series compensator (SSSC), thus it has all the capabilities of STATCOM and SSSC or TCSC at the same time and can perform all the series and shunt compensatory operations. The DC source, being shared by both the series and shunt components, is an active power source. One of the advantages of UPFC is its constant control of the phase angle, impedance and voltage value, which leads to the constant control of active and reactive power in transmission line. In the load frequency control system, UPFC is parallel to transmission line. The connection of UPFC to the sample two-area power system is shown in (Fig. 2) [21].

We have:

$$P_{active} - jQ_{reactive} = \overline{V^*}_r \, I_{line} = \overline{V^*}_r \left\{ \frac{\overline{V}_s + \overline{V}_{se} - \overline{V}_r}{j(X)} \right\} \quad (1)$$

Where

$$\overline{V}_{se} = |V_{se}| \angle(\delta_s - \emptyset_{se}) \quad (2)$$

After solving equation (1), the real part is given as below:

$$P_{active} = \frac{|V_s||V_r|}{(X)} \sin\delta + \frac{|V_s||V_{se}|}{(X)} \sin(\delta - \emptyset_{se}) = P_0(\delta) + P_{se}(\delta, \emptyset_{se}) \quad (3)$$

In this equation, if Vse=0 the system cannot compensate the real power, however series part of UPFC can control the voltage value between 0 and Vse,max, and the system can control the phase angle of voltage between 0˚ and 360˚, then we can use UPFC for LFC as follows:

$$\Delta P_{UPFC}(S) = \left\{ \frac{1}{1 + ST_{UPFC}} \right\} \Delta F(S) \quad (4)$$

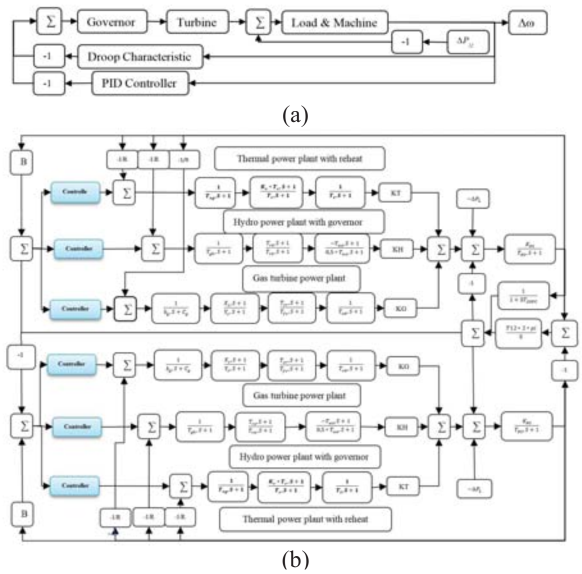


Fig. 1. a) Block diagram of a SMIB system with a PID controller. b) Block diagram of a two-area three-machine system with PID controllers.

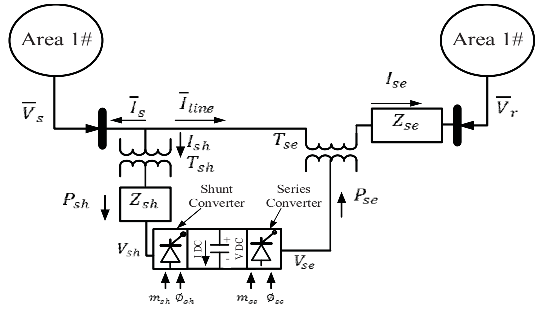


Fig. 2. Block diagram of UPFC[21].

III. Method of Problem Solving

A. Self Tuning Fuzzy Logic Controller (STFLC)

In this paper, STFLC structure is used for control purposes. The basic structure of Mamdani-type fuzzy logic controller includes four main components: fuzzification, rule base, inference engine, and defuzzification. The outline of STFLC is shown in Fig. 3. Speed error and error derivative are used as controller inputs. $K_{in}1$ and $k_{in}2$ parameters are responsible for the input signals in normal limits. These parameters are called scaling parameters of inputs. k_{out} parameter is the scaling factor of the output responsible for output scale conversion of a value calculated by the fuzzy controller. Then k_{out} parameter is applied to the system. Control signal produced by STFLC is applied as an auxiliary signal to the governor system. Previous experience in dynamics of controlled systems and evaluating the input and output waveforms are usually used in the design of rule bases of the fuzzy controller. In Table 1, the rules of the proposed fuzzy controller are provided. Membership function of input signals is considered as triangular and symmetric form in five fuzzy values: negative big (NB), negative small (NS), zero (ZZ), positive small (PS) and positive big (PB). Fig. 4 shows the membership function assigned to input signals. The allowable range of [-1, 1] has been selected for two inputs (error e(t), and its derivative Δe(t)). Mamdani's inference method and center-of-gravity defuzzification method were selected.

Membership function of output signals (P, I and D) also has five fuzzy values: small (S), medium (M), big (B), very big (VB) and very very big (VVB), and has been considered as a triangular and symmetric form. It should be noted that the membership function is related to the stage prior to optimization. In other words, the coefficients a1, a2 and a3 will be optimized. Fig. 5 shows the membership function assigned to output signals. The allowable range of outputs is selected as [0, 1]. Like inputs, Mamdani's inference method and center-of-gravity defuzzification method were selected for the outputs.

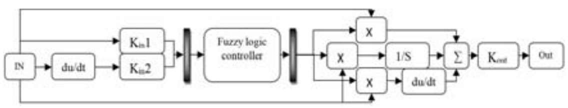


Fig. 3. The structure of proposed STFLC

TABLE I. Rule Base Table of the Proposed STFLC

e \ e dot	*NB*	*NS*	*ZZ*	*PS*	*PB*
NB	S	S	M	M	B
NS	S	M	M	B	VB
ZZ	M	M	B	VB	VB
PS	M	M	VB	VB	VVB
PB	B	VB	VB	VVB	VVB

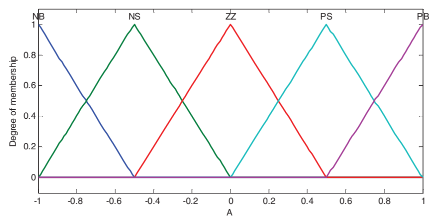


Fig. 4. Membership function of two inputs

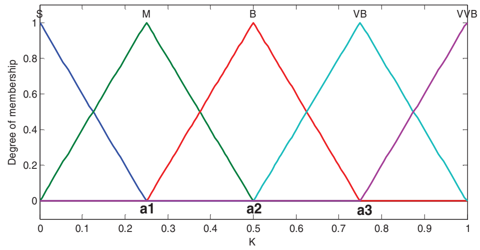


Fig. 5. Membership function of three outputs without optimized a1, a2, a3

B. Teaching Learning Based Optimization

TLBO algorithm is based on the teaching of a teacher in the classroom [23]. The teacher expressing course material in the classroom has a significant role in student learning and better student learning depends on the teacher's type of expression. In addition to the influence of the teacher, review of course materials also leads to a better learning. This idea is the base of TLBO algorithm for solving optimization problems. The performance mechanism of TLBO algorithm consists of two parts: the first part is the teacher's share in improving the scientific level of the class and the second part is the interaction and course material review by the students of the same class.

1) The teacher share

A good teacher is someone who brings the knowledge level of a class closer to his/her own level. In practice, the knowledge level of the students will not be the same as the teacher's knowledge level and will only be close to it (an amount approaching it depends on the level of the class ability). This part has been modeled as below:

$$\overline{X}_{diff}^{k} = rand(\quad) \times (T^k - R_t \times M^k) \tag{5}$$

where T^k is the teacher's level in k^{th} iteration, Mk is the average of the class level in k^{th} iteration, R_t is a teaching coefficient that is zero or one and will be randomly selected in each iteration. Also $\overline{X}_{diff}^{k}$ is the difference between the teacher and the student's knowledge level. Population in the next iteration is made as follows:

$$\overline{X}_{new}^{k+1} = \overline{X}_{old}^{k} + \overline{X}_{diff}^{k} \tag{6}$$

where $\overline{X}_{old}^{k}$ is the same member of the population in previous iteration and $\overline{X}_{new}^{k+1}$ is a new member of the population. Here, a cost function is defined for the new member of the population. The cost function value is compared to the cost function value obtained from the same member of population in the previous iteration ($\overline{X}_{old}^{k}$). If it is lower, the old member will be replaced by the new member.

2) The Student Share

Students will increase the level of their knowledge in two ways. One, by the attendance and use of the teacher's knowledge in the classroom and also by the review of the course between themselves and other students. For modeling, it is assumed that each student's knowledge is randomly exchanged with another student's and its mathematical model is defined as below:

$$\overline{X}_{new} = \overline{X}_{old} + rand(\quad) + \left(\overline{X}_i - \overline{X}_j\right) \tag{7}$$

where $\overline{X}_i$ and $\overline{X}_j$ are *i*th and *j*th (student) member of the population, $\overline{X}_{old}$ is an old member of the population and $\overline{X}_{new}$ is a new member of the population. After calculating the new member of the population, its cost function value is compared to the one obtained from the previous iteration. If the new amount is lower, the new member will be replaced. This process is repeated up to a certain number. A more detailed description of the TLBO algorithm is available in [22-23].

In order to evaluate the performance of the proposed optimization method, simulation using MATLAB software is done on the basis of a performance index. Performance index is generally defined as a function of system variables. Extremum (maximum or minimum) of the above index will result in achieving an optimal set of the system parameters.

Since the purpose of applying the STFCL in a system is to reduce electromechanical oscillations, the integral of time-absolute error (ITAE) of area control error (ACE) is used in accordance with equation (5) which is the sum of the ITAE of both areas 1 and 2. ACE_i is defined as follows:

$$ACE_i = \Delta P_{tie,i} + B_i \Delta f_i \tag{8}$$

where $\Delta P_{tie,i}$ is gradual change in the tie-line power between area i and other areas, Bi is frequency bias settings of area i, and Δf_i is gradual change in the frequency of area i.Another criterion is used here is called the integral of time multiply squared error (ITSE). The difference between ITAE and ITSE criteria is that in ITSE criterion the reduced error absolute is more important at all times than reducing oscillations over time. On the other hand, the maximum value of ACE is considered as the third objective function of the problem.

In this paper, the performance index is defined as the sum of the three above functions as it is shown in the following and its purpose is to minimize its value to obtain the value of input and output scales:

$$O.F = w_1F_1(X) + w_2F_2(X) + w_3F_3(X)$$

$$F_1(X) = ITAE = \int_0^{t_{sim}} t.(|ACE_1| + |ACE_2|.dt \tag{9}$$

$$F_1(X) = ITSE = \int_0^{t_{sim}} t.((ACE_1)^2 + (ACE_2)^2).dt$$

$$F_3(X) = -\max(ACE_1) - max(ACE_2)$$

where w_1, w_2 and w_3 are respectively the weighting coefficients of the ITAE and ITSE criteria and maximum value of ACE and their value is respectively equal to 10, 1, and 100. Constraints related to the optimization problem are also defined as follows:

$$K_{1imin} \leq K_{1i} \leq K_{1imax}$$
$$K_{2imin} \leq K_{2i} \leq K_{2imax}$$
$$K_{3imin} \leq K_{3i} \leq K_{3imax}$$
$$a_{1imin} \leq a_{1i} \leq a_{1imax}$$
$$a_{2imin} \leq a_{2i} \leq a_{2imax}$$
$$a_{3imin} \leq a_{3i} \leq a_{3imax}$$

In the TLBO algorithm, any solution of controller design problem is a string of integer numbers, each of which indicates the input and output scales and a1, a2 and a3 values. Therefore, the number of digits is 6 for each fuzzy controller. According to the TLBO algorithm, students are affected by the best student or teacher and progress. In the proposed method, each poor student finds some tendency towards the strong student or teacher. This rate is determined by a random number (Fig. 6).

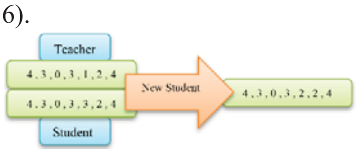


Fig. 6. Selection of a new student in the proposed algorithm.

As noted above, the coefficients a1, a2 and a3 and input scales (which are 3 numbers) should be optimized for the fuzzy controller. After optimization, membership functions for three inputs P, I and D are shown in Figure 7. As it can be seen, these functions have a significant difference with each other and with the not-optimized membership function.

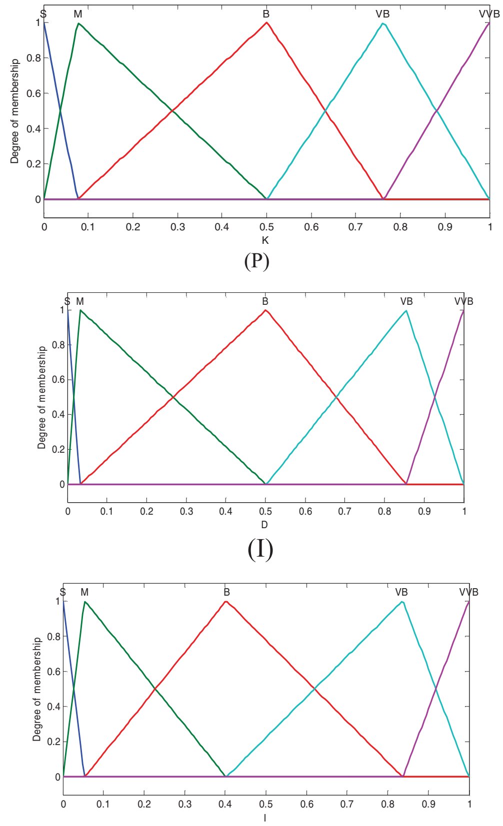


Fig. 7. Output membership function (P, I, and D) after optimization

Input and output scales of the controllers obtained from the TLBO algorithm for both areas are shown in Table 2. Also the optimized values of parameters a1, a2 and a3 related to the PID fuzzy controllers are shown in Table 3.

TABLE II. OPTIMAL PARAMETERS OF STFLC OBTAINED FROM TLBO

Parameters	Area 1			Area 2		
	Thermal	**Hydro**	**Gas**	**Thermal**	**Hydro**	**Gas**
K_{in1}	10	9.6714	10.0	0.0001	6.7519	10
K_{in2}	0.0001	4.7245	3.4025	10	0.0001	4.1838
K_{out}	10	0.0001	9.9757	10	0.0001	10

TABLE III. THE RESULT OF THE OPTIMIZATION OF STFLC BY TLBO

Parameters	Output of Fuzzy PID		
	P	*I*	*D*
a1	0.3	0.2994	0.3
a2	0.7	0.7	0.7
a3	1.0	1.0	1.0

IV. SIMULATION RESULT

The fuzzy controller designed above is applied to both areas of a three-machine power system. The simulation of the system is done in MATLAB software and its fuzzy logic toolbox. The system responses to the optimized PID, optimized fuzzy controller, and optimized fuzzy controller with UPFC have been compared with that of the not-optimized fuzzy controller and the results are shown in Figs. 7-10, respectively for 1% and 15% disturbance in the load of area#1, and 1% and 15% change in the load of area#2. The Integral Time Absolute Error (ITAE) criterion in the STFLC in comparison with the TLBO optimized PID controller has indicated improvement levels of 55% (1), 55.75% (2), 56% (3) and 36.5% (4). In addition, the OSTFLC in comparison with the STFLC showed improvement levels of 23.2% (1), 26.4% (2), 30% (3) and 33.8% (4). On the other hand, the OSTFLC and UPFC together have also worked better than OSTFLC with the improvement levels of 28% (1), 27% (2), 20.5% (3) and 11% (4). The Integral Time Square Error (ITSE) criterion in the STFLC in comparison with the TLBO optimized PID controller has indicated improvement levels of 51.8% (1), 81% (2), 77% (3) and 57.7% (4). In addition, the OSTFLC in comparison with the STFLC showed improvement levels of 3% (1), 47% (2), 50.5% (3) and 53% (4). On the other hand, the OSTFLC and UPFC together have also worked better than OSTFLC with the improvement levels of 38% (1), 39.7% (2), 38.5% (3) and 30.5% (4). From these results, it is clear that the OSTFLC can more quickly damp oscillations and control the load frequency than the not-optimized fuzzy controller. OSTFLC with UPFC is more effective than OSTFLC without UPFC.

TABLE IV. COMPARISON OF PERFORMANCE INDICES FOR THE FOUR CASE STUDIES IN THE STUDIED 2-AREA POWER SYSTEM

Case study	ITAE				ITSE			
	TLBO-PID	STFLC	OSTFLC	OSTFLC-UPFC	TLBO-PID	STFLC	OSTFLC	OSTFLC-UPFC
ΔPD1=1% ,ΔPD2=0%	0.0652	0.0293	0.0225	0.0162	0.000056	0.000027	0.0000262	0.00001626
ΔPD1=0% ,ΔPD2=1%	0.0599	0.0265	0.0195	0.0142	0.000156	0.0000295	0.0000156	0.0000094
ΔPD1=2.5% ,ΔPD2=5%	0.4538	0.1981	0.1385	0.1101	0.0081	0.0018	0.00089	0.0005468
ΔPD1=5% ,ΔPD2=10%	0.6499	0.4182	0.2769	0.2466	0.0182	0.0077	0.0036	0.0025

TABLE V. THE VALUES OF THE OVERSHOOT AND THE UNDERSHOOT IN THE FREQUENCY OUTPUT OF AREA 1#

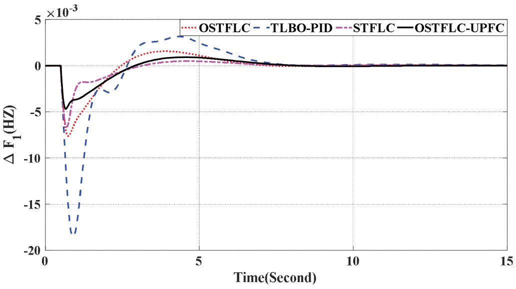
Case Study	Frequency division in Area 1#							
	TLBO-PID		STFLC		OSTFLC		OSTFLC-UPFC	
	US(-)	OS	US(-)	OS	US(-)	OS	US(-)	OS
ΔPD1=1% ,ΔPD2=0%	0.0185	0.0016	0.0076	0.0004996	0.0066	0.0032	0.0047	0.000924
ΔPD1=0% ,ΔPD2=1%	0.01	0.0017	0.0017	0.000149	0.0031	0.0008	0.002	0.0004869
ΔPD1=2.5% ,ΔPD2=5%	0.0565	0.0174	0.0168	0.0019	0.0251	0.0079	0.0160	0.0043
ΔPD1=5% ,ΔPD2=10%	0.1115	0.0169	0.0311	0.0086	0.0486	0.0177	0.0319	0.0046

TABLE VI. THE VALUES OF THE OVERSHOOT AND THE UNDERSHOOT IN THE FREQUENCY OUTPUT OF AREA 2#

Case Study	Frequency division in Area 2#							
	TLBO-PID		STFLC		OSTFLC		OSTFLC-UPFC	
	US(-)	OS	US(-)	OS	US(-)	OS	US(-)	OS
ΔPD1=1% ,ΔPD2=0%	0.01	0.0017	0.0063	0.0017	0.0031	0.000797	0.002	0.0004869
ΔPD1=0% ,ΔPD2=1%	0.0185	0.0032	0.0077	0.0023	0.0076	0.0016	0.0047	0.000924
ΔPD1=2.5% ,ΔPD2=5%	0.0860	0.0204	0.0464	0.0168	0.0386	0.0098	0.0239	0.0054
ΔPD1=5% ,ΔPD2=10%	0.2067	0.0249	0.0946	0.0390	0.0718	0.0220	0.0478	0.0107

TABLE VII. THE VALUES OF THE OVERSHOOT AND THE UNDERSHOOT IN TIE LINE

Case Study	Power division in tie line							
	TLBO-PID		STFLC		OSTFLC		OSTFLC-UPFC	
	US(-)	OS	US(-)	OS	US(-)	OS	US(-)	OS
ΔPD1=1% ,ΔPD2=0%	0.0024	0.0002892	0.0021	0.0004287	0.0010	0.0001842	0.0007247	0.000141
ΔPD1=0% ,ΔPD2=1%	0.00029	0.0024	0.0000468	0.000567	0.000183	0.0011	0.000141	0.0007247
ΔPD1=2.5% ,ΔPD2=5%	0.000765	0.0048	0.0026	0.0018	0.00047	0.0028	0.000352	0.0018
ΔPD1=5% ,ΔPD2=10%	0.0049	0.0117	0.0036	0.0033	0.0011	0.0057	0.0007	0.0036



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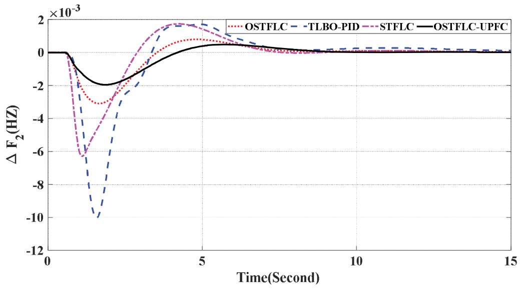

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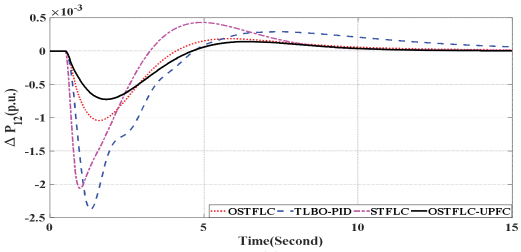
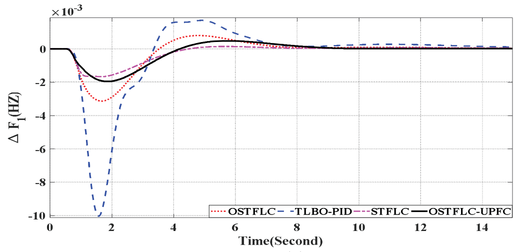


(c)

Fig. 8. Frequency and tie-line power variations due to 1% disturbance in the load of area#1 in case study 1.



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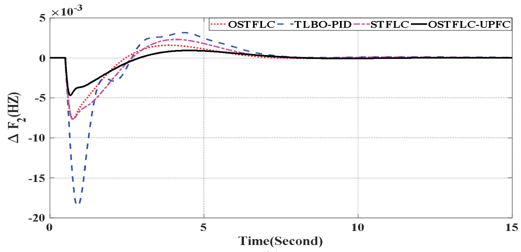

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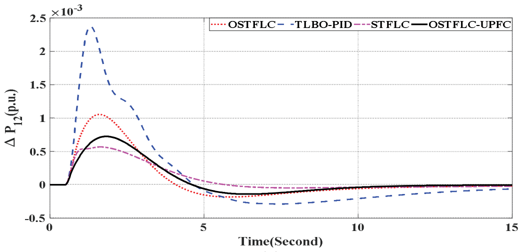
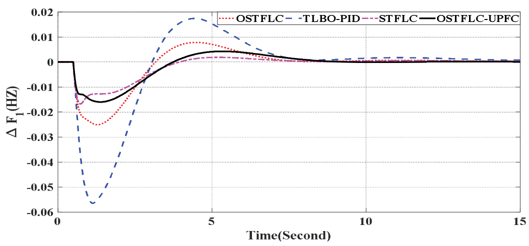
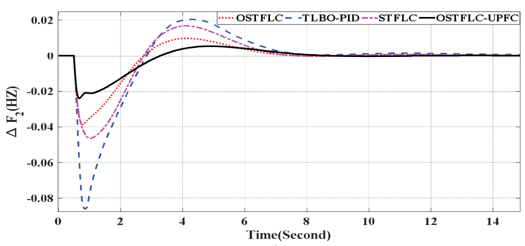


(c)

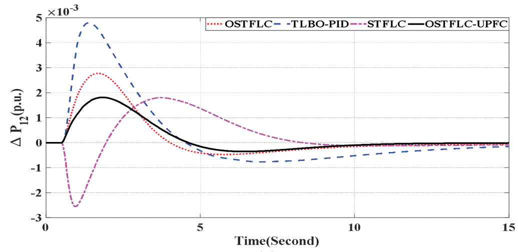
Fig. 9. Frequency and tie-line power variations due to 1% disturbance in the load of area#2 in case study 2.



(a)

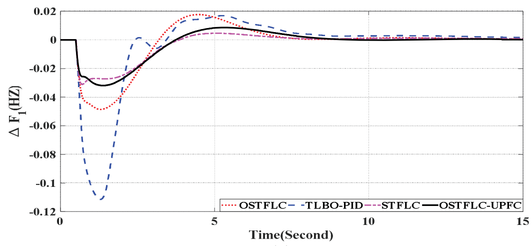


(b)

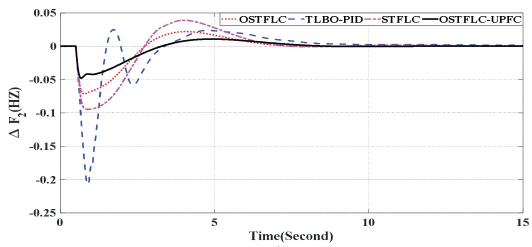


(c)

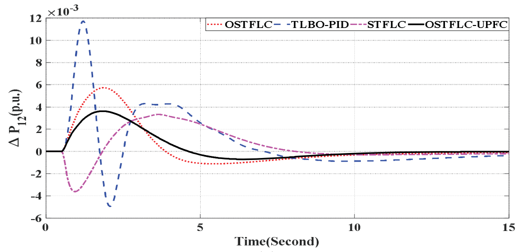
Fig. 10. Frequency and tie-line power variations due to 15% disturbance in the load of area#1 in case study 3.



(a)



(b)



(c)

Fig. 11. Frequency and tie-line power variations due to 15% disturbance in the load of area#2 in case study 4.

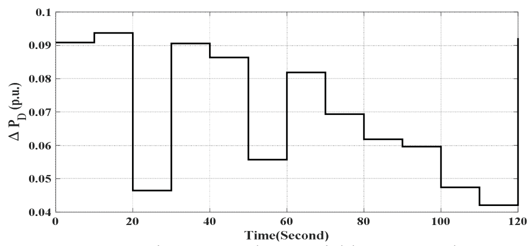


Fig. 12. Random Variable Step Load

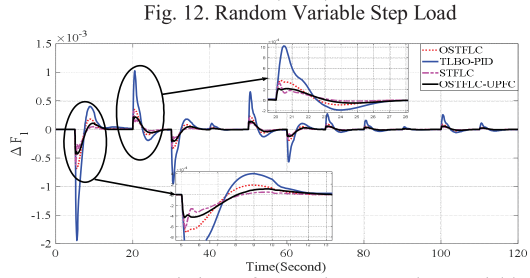


Fig. 13. Frequency variations of area 1 due to Random Variable Step Load

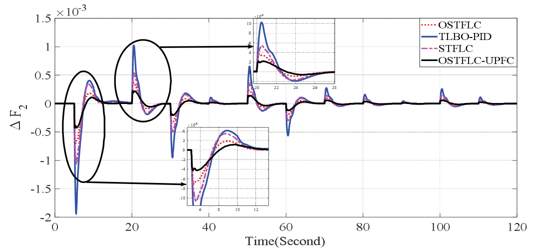


Fig. 14. Frequency variations of area 2 due to Random Variable Step Load

V. CONCLUSION

In this paper, the design and operation of the load frequency control of a two-area three-machine power system with self-tuning fuzzy controllers were studied. In order to improve the fuzzy controller performance, two input scales, one output scale and three PID membership functions were optimized by a TLBO algorithm. The objective of the optimization problem was based on the minimized criteria including ITAE, ITSE and a maximum of Area Control Error (ACE). The optimized controller performance was compared with that of a not-optimized controller under a variety of electrical loads of both areas. Using UPFC has a positive effect on optimized fuzzy PID and the system response. The parameters compared in this study include area frequency and tie-line power responses, ITAE, ITSE, undershoot (US) and overshoot (OS). This comparison shows very superior performance for the optimal fuzzy controller in the load frequency control of power systems.

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Appendix

The typical values of the system under study are given below:

f= 60 Hz; $B_1=B_2$= 0.4312 pu MW/Hz; P_R= 2000 MW (rating), P_L= 1840 MW (nominal loading); $R_1=R_2=R_3$= 2.4 Hz/pu MW; T_{sg}= 0.08 s; T_r=10s; K_r= 0.3; T_t= 0.3 s; K_T= 0.543478; K_H= 0.326084; K_G= 0.130438; T_{gh}= 0.2 s; T_{rh}= 28.75 s; T_{rs}=5s; T_W=1s; bg= 0.5; cg=1; Xc= 0.6 s; Yc=1s; T_{cr}= 0.01 s; T_{fc} = 0.23s; T_{cd}= 0.2 s; T_{ps}= 11.49 s; Kps= 68.9566 Hz/pu MW; T_{12}= 0.0433