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Proceeding Paper

TLBO Tuned a Novel Robust Fuzzy Control Structure for LFC of a Hybrid Power System with Photovoltaic Source [†]

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Abstract: This study proposes a new fuzzy logic control (FLC) design-based I controller plus a Fuzzy Cascade FOPI-FOPD (I + F C FOPI-FOPD) for load frequency control (LFC) in power systems. The structure of this design offers a satisfactory level of reliability as well as excellent robustness performance. The proposed fuzzy design is employed in a hybrid dual area power system based on a photovoltaic renewable energy plant in area one and a thermal generation unit in area two. In order to achieve the best possible dynamic performance of the proposed structure, the teaching learning-based optimization (TLBO) algorithm is suggested to optimally tune the scaling factor gains of the proposed fuzzy configuration. The superiority of the suggested fuzzy control design is investigated by conducting a comparative study between this design and a previously applied PI-based firefly algorithm. Simulation results revealed that the fuzzy logic controller introduced in this study is reliable and superior, and appropriately handled the problem of frequency variation.

Keywords: fuzzy logic control (FLC); load frequency control (LFC); dual area power system; teaching learning-based optimization (TLBO)

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1. Introduction

Modern power systems are becoming more reliant on renewable energy resources (RERs). The dependence on RERs is mainly due to the continuous increments in the prices of fossil fuels in addition to avoiding the emission of greenhouses gases and its obvious link to the global warming dilemma. Moreover, the fact of the increasing power demand in today's world means there is a requirement for a huge number of different generating units to interconnect through existing transmission lines called tie-lines to meet the increasing power consumption; this also leads to the adoption of hybrid power systems where electrical networks rely on RERs along with the traditional power resources. The RERs used in interconnected power systems may be photovoltaic (PV), wind turbine (WT), energy storage system, fuel cell (FC) with electrolyser and battery. Solar and wind energy resources have been considered the most commonly used in power systems among the various RERs. However, many modern power systems remain reliant on thermal generation to meet the demands of end users. This gives an obvious idea of the vital role that thermal units play in power systems in addition to the continued increase in RERs reliance [1].

From a control engineering point of view, ensuring the stable and reliable operation of modern power systems is one of the most challenging processes. This is due to the continuous increase in their size, which in turn leads to more complexity in addition to having to consider the external/internal disturbances that power systems unpredictably experience.

Furthermore, load demand in most power systems is continually changing and this change leads to consequences of a deviation in frequency and tie-line power flow and, in turn, requires a similar change in the generation side. Accordingly, the mismatch between the demanded power and the generated power is the reason for the frequency and tie-line power deviations throughout the whole power system. Importantly, in stable, secure and reliable power systems, the frequency and tie-line power flow are maintained in their pre-specified limits in normal operating conditions as well as in case of a sudden disturbance occurrence, which is achieved by balancing the active power output of the generated power and the requested demand plus the possible losses. This control mechanism is called load frequency control (LFC). As a result of installing this loop-LFC in power systems, frequency and tie-line power deviations are guaranteed to be always zero or within acceptable limits. Based on this, an improper LFC system design may undermine the overall behaviour of the controlled system causing undesired fluctuations in frequency and tie-line flow, which in turn may lead to system instability [2].

Due to the above-mentioned issues, incorporating LFC in power systems based on different generating sources has become the most significant research area to focus on. To overcome this issue, many researchers presented different approaches to simulate LFC integrated into different power systems. Traditional control techniques, robust control methods, sliding mode control and artificial controllers have been applied in this field. In [3], a PI controller-based firefly optimization algorithm was designed and implemented for LFC in a dual area interconnected power system incorporating a PV system. A PI controller tuned by the Harris Hawks optimizer-based LFC in two different power systems with RERs was successfully implemented to regulate the frequency in the case of sudden load disturbance [4]. A movable damped wave algorithm tuned Fractional Order (FO) PID was equipped as an LFC system in two and four area interconnected power systems with PV and WT plants, and the FOPID-based proposed algorithm outperformed the same controller tuned by other optimization techniques [5]. Another application of a FOPID in LFC for power systems with RERs was suggested in [6]; in this study, a modified hunger games search optimizer was proposed to find the optimal values of the FOPID's gains. An adaptive PI-based LFC system installed in two different dual area power systems was proposed in [7]; the suggested controller evidenced its superiority over the traditional PI. LFC-based sliding mode control (SMC) was proposed in [8] for a hybrid power system incorporating WT and energy storage systems. A new SMC based on the disturbance observer was suggested in [9] for LFC in a hybrid power system considering the presence of WT, system parametric uncertainty and non-linear restraints. A linear matrix inequality-based particle swarm (PSO) optimization algorithm was proposed in [10] to stabilize the frequency in a power system with different energy resources. A model predictive control approach was also proposed for frequency stabilization in a hybrid power system consisting of different plants including WT [11].

Notably, in recent years, LFC-based fuzzy logic control has received considerable attention. This is due to the wide range of merits offered by this controller. Furthermore, soft computing techniques have been exploited to achieve the best possible dynamic performance of FLC. Fuzzy PID with a filtered derivative action optimized by the Bees algorithm has been successfully implemented as an LFC system in a simplified form of the Great Britain power system [12]. Different fuzzy structures were proposed in [13] to damp the frequency/tie-line power variations in a two-area power system. In this study, the proposed fuzzy PI plus Fuzzy PD illustrated a slight supremacy over the other investigated configurations. A fuzzy cascade FOPI-FOPD-based PSO for LFC purposes in a multi-area electrical system was studied in [14]. Another application of FLC-based frequency regulation was investigated in [15]; in this study the proposed controller was installed in a two-area multi-source power system with a PV unit, WT and redox flow battery, and successfully damped the frequency deviation under various operating conditions. In [16], an adaptive fuzzy FOPID was implemented for LFC in the renewable penetrated electrical power network.

Notwithstanding the fact that the above-mentioned techniques have different merits and successfully solved the problem of frequency deviation to a great extent, it is noteworthy to mention the limitation of installing these techniques in power systems. For example, the traditional controllers are known not to provide the required response when the controlled system undergoes possible operating conditions of non-linearities or high sensitivity. However, the low cost is the main advantage of classical controllers. In terms of other controllers such as adaptive control and SMC, although they offer an effective performance as LFC systems, the complexity in their design and high computational time and burden are known as the most common limitations. Furthermore, some useful studies have proposed and applied different structures of fuzzy control for frequency regulation; however, most of these techniques lack the consideration of reliability in the design.

Therefore, the authors of this paper propose a novel FLC configuration that guarantees a high level of reliability for LFC in a dual area power system incorporating a PV unit. The suggested technique is an I controller plus Fuzzy Cascade FOPI-FOPD (I + F C FOPI-FOPD). Moreover, to obtain the best performance from the suggested controller, a well-known/powerful optimization tool called the teaching learning-based optimization algorithm is used in this work to optimally set the parameters of the proposed I + F C FOPI-FOPD. Furthermore, the strong performance of this controller is evidenced by comparing the results with those based on the PI optimized by the firefly algorithm studied in [3].

2. Power System under Study

In this study, a two-area interconnected power system is considered to demonstrate the effectiveness of the proposed fuzzy controller for LFC purposes.

As shown in Figure 1, this system consists of a PV plant equipped in area one and a thermal unit installed in area two. This system has extensively been used in the literature [3,7]. The values of the parameters of the investigated system are as follows

$$C_1 = -18, C_2 = 900, C_3 = 100, C_4 = 50$$
$$T_g = 0.08, T_t = 0.18, K_r = 3.3, T_r = 10, K_p = 120, T_p = 20 \text{ and } T = 0.545.$$

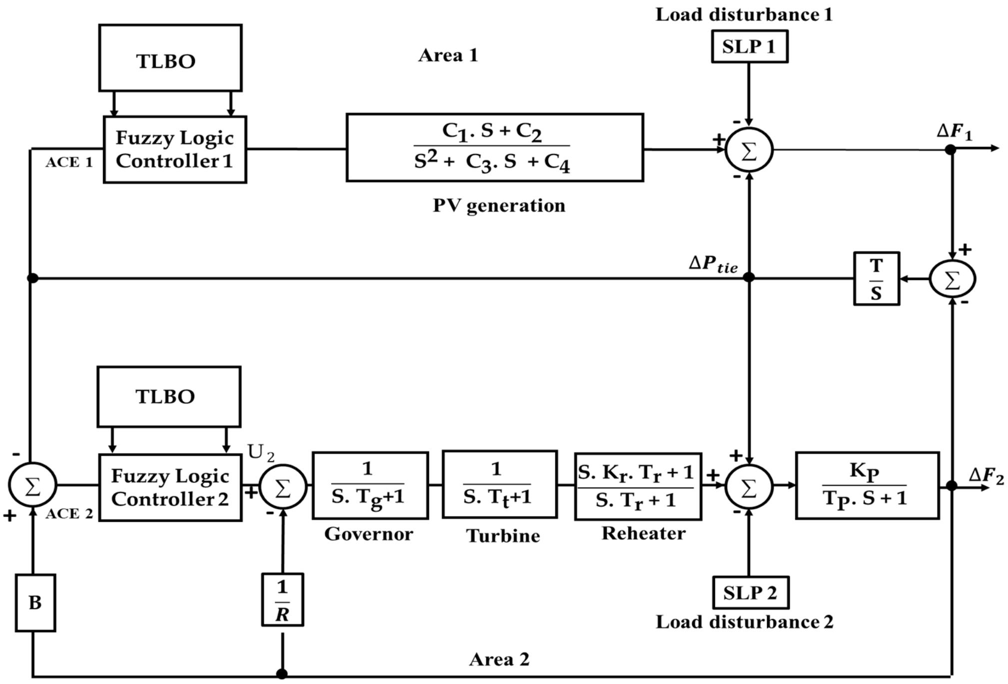

Figure 1. The testbed dual area power system.

3. The Proposed LFC System

As above-mentioned, this study develops and implements a new fuzzy configuration in order to achieve the required level of reliability.

3.1. I Controller Plus Cascade Fuzzy FOPI-FOPD

Figure 2 demonstrates the structural diagram of the proposed controller. This controller comprises two parts; a fuzzy cascade FOPI-FOPID enhanced with a classical I controller. As is obvious, the fuzzy part has two inputs: "the Area Control Error (ACE) and change of ACE" in addition to one output. The output signal of the fuzzy controller is connected with the input of the FOPI. However, the input signal of the latter controller "FOPD" is the output signal of the FOPI in addition to the ACE signal. Finally, the output signal of FOPD is added to the output of the classical I, which in total represent the control signal of the proposed controller. The rule bases of the fuzzy controller are given in Table 1, while the membership function of the inputs and the output are illustrated in Figure 3.

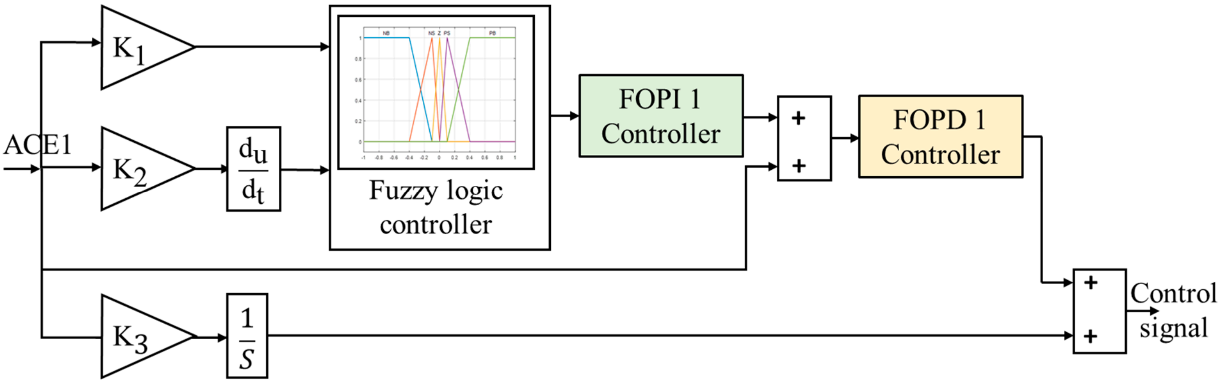

Figure 2. The diagram of the proposed I plus fuzzy cascade FOPI-FOPD.

Table 1. Fuzzy role bases.

ACE 1	**ACE 1**				
	NB	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

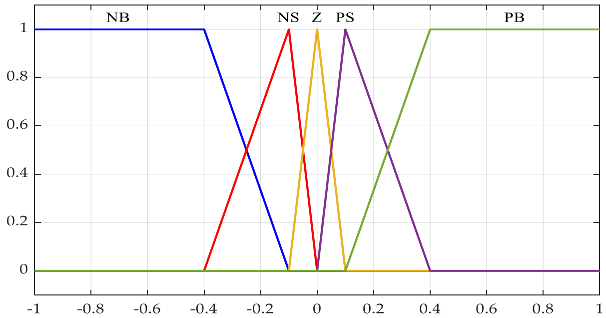

Figure 3. Membership functions of inputs/output.

3.2. The Optimisation Tool-TLBO and the Objective Function

In order to enhance the performance of the proposed LFC system, the values of its parameters are found by employing the TLBO by minimizing the Integral Time Absolut

Error (ITAE) of the frequency deviation in both areas and the tie-line power fluctuation (see Equation (1)). The mechanism and the variants of the suggested TLBO are given in [17].

$$\text{Objective Function} = \text{ITAE} = \int_0^t (|\Delta F_1| + |\Delta F_2| + |\Delta P_{tie}|).t.\, dt \tag{1}$$

4. Results and Discussion

The proposed controller is equipped in the system, with a controller in each area; then a load disturbance of 0.1 pu is applied in area two. The optimal values of the controller obtained by TLBO are given in Table 2. The frequency deviation in areas one and two and the tie-line power fluctuation are given in Figures 4–6, respectively, in addition to Table 3. Additionally, these figures provide a comparison between the results obtained via the proposed fuzzy controller and the results from the PI tuned by FA. Figures 4–6 and Table 3 reveal the effectiveness and superiority of the proposed fuzzy controller. This controller successfully met the requirements of LFC systems and provided excellent responses in all aspects.

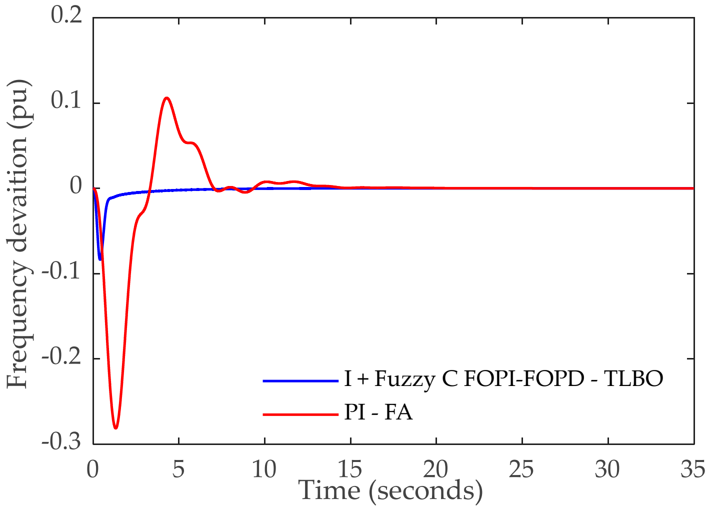

Figure 4. Frequency drop in area one.

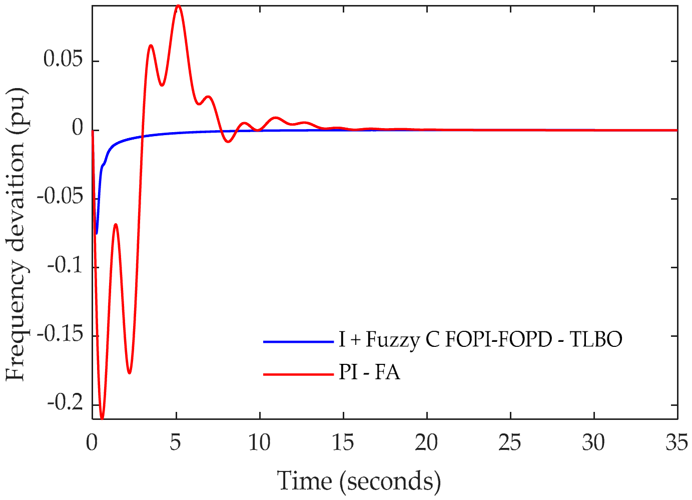

Figure 5. Frequency drop in area two.

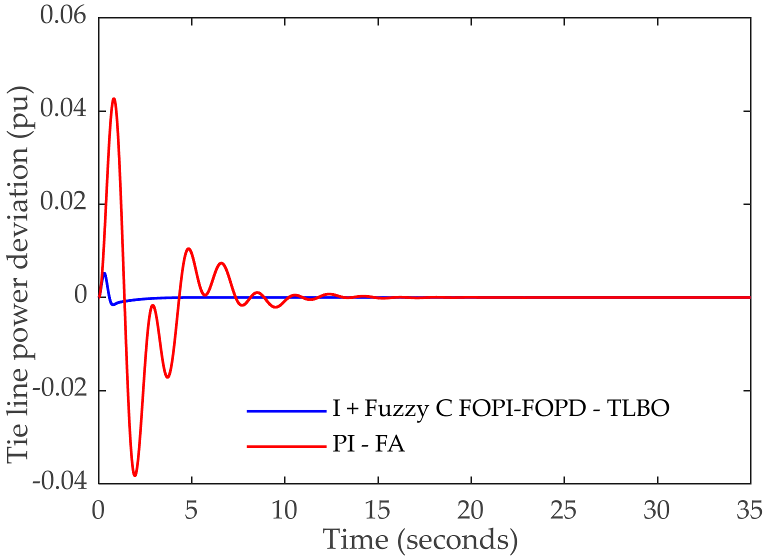

Figure 6. Tie-line power deviation.

Table 2. The optimum values of the I plus fuzzy C FOPI-FOPD.

Controller	**Parameters**								
Area one controller	K_1 0.284	K_2 0.7304	K_3 −1.9193	K_{P11} 0.5200	K_{I1} 0.4816	λ_1 0.6971	K_{P12} −1.6179	K_{D1} 0.7885	μ_1 0.1499
Area two controller	K_4 −1.28	K_5 −0.1798	K_6 −2	K_{P21} −2	K_{I2} 0.0409	λ_2 0.1631	K_{P22} −1.6188	K_{D2} 0.0142	μ_2 0.2625

Table 3. The dynamic response of the system with the proposed controller.

Controller	**Frequency in Area One**			**Frequency in Area Two**			**Tie-line Power Deviation**			**ITAE**
	U_{sh} in pu	**O_{sh} in pu**	**T_s in s**	**U_{sh} in pu**	**O_{sh} in pu**	**T_s in s**	**U_{sh} in pu**	**O_{sh} in pu**	**T_s in s**	
I + F C FOPI-FOPD	−0.0835	0	5.697	−0.0751	0	5.9810	−0.0015	0.0052	3.3810	0.267
PI—FA	−0.281	0.106	12.283	−0.210	0.0908	13.1132	−0.0382	0.0427	9.9657	4.192

5. Conclusions

Concisely, this paper developed and implemented a virgin fuzzy control structure named I plus fuzzy cascade FOPI-FOPD employed as an LFC system in a dual area power system incorporating a PV unit in area one. This controller significantly damped the frequency deviation in both areas and also outperformed the previously proposed PI controller-based FA.

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