# Teaching-Learning Optimization Based Adaptive Fuzzy Logic Controller for Frequency Control in an Autonomous Microgrid

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**Abstract-** This paper addresses teaching learning optimization based adaptive fuzzy logic controller (AFLC) for frequency control in an autonomous AC microgrid. This autonomous microgrid consists of various renewable energy sources like PV and Wind power with high degrees of nonlinearities and also with variable load disturbances which can significantly, influences the system frequency. By considering all these uncertainties, the microgrid frequency control problem faces new challenges. Controlling of microgrid in autonomous mode is becoming a difficult task than in grid connected mode. In this paper novel AFLC is proposed for secondary frequency control. In proposed controller fuzzy input and output membership functions (MFs) scaling factors are tuned in online according to operating conditions using teaching learning based optimization technique (TLBO). In present work diesel engine generator is responsible for generation-load balance (secondary frequency control) in microgrid (MG). The robustness of the proposed controller is compared with conventional PI controller, fuzzy PI controller and PSO tuned fuzzy PI controller.

**Keywords** Microgrid, adaptive fuzzy logic controller, teaching-learning based optimization, frequency control.

## 1. Introduction

The increasing need of electrical energy for remote locations like islands & rural areas is becoming necessary in to-days power system. Power supply from grid is costly and environmental hazard, such problems are made autonomous microgird is reliable and efficent solution. Many countries like Japan, South Africa, China et.al installed microgrids for providing electrical energy in remote locations [1-2]. These microgrids consist of several renewable energy sources, which will supply highly nonlinear variable power. Therefore microgrid control in autonomous mode is difficult than in grid connected mode. Due to more interaction of renewable energy sources these microgrids experiences low system inertia and high nonlinear power fluctuations. This will cause large frequency fluctuations in microgrids and system loses its stability. Considering all the above factors, the microgrids require efficient and intelligent controllers to control the frequency within the tolerable limits.

Conventional control method for secondary frequency control problem is injecting a restorative control signal to governor summing point utilizing PI/PID controllers. But this controller fails to keep frequency variations within tolerable limits because of high non linear nature of various sources, loads and with low system inertia. Several authors proposed different methods to tune PI/PID controllers for load frequency control problem [3-6]. Similar to conventional power plants, load frequency control for microgrid is done with various hierarchical controls (Primary, Secondary & Tertiary frequency control) are proposed by several authors [7-19]. In [7- 9] the papers proposes supplementary load frequency control by using electrical vehicles and heat water pumps for improving primary frequency control . In [10] the authors proposed non disruptive based frequency control for real-time system and in this method; controller initially works in load restoration mode (during transient response). Initially, once the frequency attains within the tolerance limit, the controller will act in frequency restoration mode. In general, microgrid consists of renewable sources, diesel engine generators (DEGs) and micro turbine (MT), DEGs & MT would take care the frequency control in MG. In order to reduce the burden and also to enhance the control efforts of DEGs and MTs, coordinated control with energy storage elements is proposed in [11-15].

In[16-18] various controllers for secondary frequency control of various MGs are proposed. In [16] H∞ based robust controller for hybrid MG is presented. PSO based linear matrix inequality controller is proposed for interconnected MG and compared with GA in [17]. In [18] adaptive fuzzy logic based PI controller is proposed for islanded MG operation in which fuzzy logic membership functions optimally tuned by using PSO and the results are compared with the fuzzy PI controller. But problem with PSO is its performance is highly dependence on their controlling parameters (inertia weight, cognitive parameter).

Since, last 5 to 6 years several authors proposed different control strategies for secondary frequency control for MGs. In that two main control strategies are identified i.e. a) centralized b) decentralized structures. In general for autonomous MG control, centralized structure is suitable and the other is suitable for grid connected MG. An intelligent and efficient secondary frequency control of an autonomous MG is the aim of this paper. This paper addresses adaptive fuzzy logic control strategy in solving frequency regulation problem. First TLBO technique is used in online to determine the optimal MFs, with this optimal MFs a new fuzzy logic controller (FLC) is obtained. Hence, this fuzzy logic controller is now termed as AFLC. To demonstrate the supremacy of the proposed AFLC, the results are compared with the various control strategies.

## 2. AC Microgrid

This paper addresses the frequency control of an autonomous AC MG including DEG, WTG, PV, BESS and Fuel cells. Lineralized model of MG structure is shown in Fig.1[18].Power balance equation of MG can be written as

$$P_{Load} = P_{DEG} + P_{WTG} + P_{PV} + P_{FC} \pm P_{BESS} \quad (1)$$

In general output power produced by the WTGS and PVS depends on environmental conditions, so there is an uncertainty in output power, because of this reason these are not used in frequency regulation problem. For frequency regulation, DEG and fuel cells are considered. An expression for the change in output power for frequency regulation can be written as follows:

$$\Delta P_{DEG} + \Delta P_{FC} \pm \Delta P_{BESS} = \Delta P_{WTG} + \Delta P_{PV} + \Delta P_{Load} \quad (2)$$

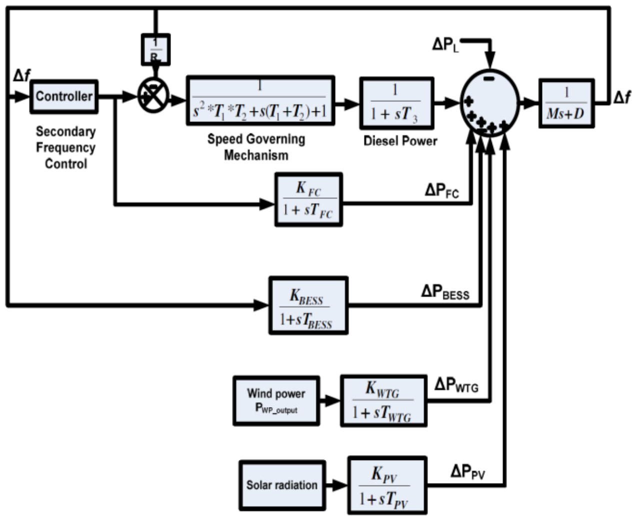



**Fig.1.** Frequency response model of the autonomous MG.

### *2.1 Diesel Engine Generator*

Diesel engine generator works, independently to supply deficiency of power in autonomous MG to maintain generation load balance. Deficiency of power for a particular load demand is met by the DEG depending on wind power and PV generations. Transfer function model of DEG for frequency control is shown in Fig.2.

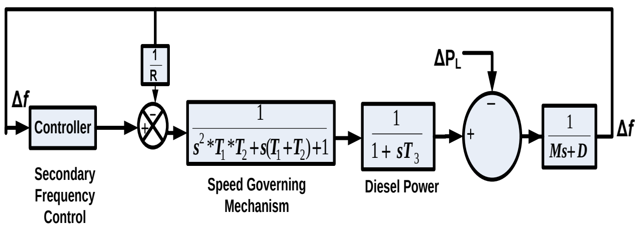



**Fig.2.** First order transfer function model of diesel engine generator.

### *2.2 Wind Turbine Generator (WTG)*

The WTG output power depends upon the wind speed and the wind speed is random in nature. The mechanical power output is written as[19]:

$$P_{WP} = \frac{1}{2}\rho\Pi r^2 C_p(\lambda,\beta)V_w^3 \quad (3)$$

Where 'r' is the radius of blade; $V_w$ is the wind velocity; $C_p$ is the power coefficient, ρ is the air density. Wind turbine uses pitch controller for minimizing the frequency oscillations according to utility grid requirements. WTG output power varies and it introduces nonlinearity in the system. However, the first order transfer function of WTG by neglecting all nonlinearities is used and as shown in Fig.3.

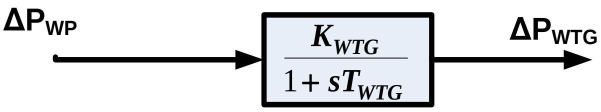



**Fig.3.** First order transfer function model of WTG

Wind power fluctuations are obtained from white noise block with some manipulations in SIMULINK as shown in Fig.4.

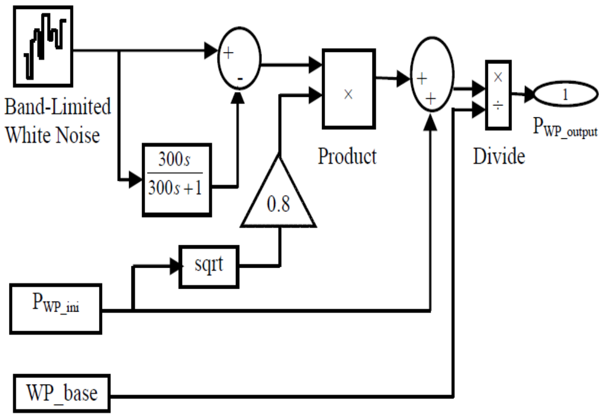



**Fig. 4.** Simulink model of wind power output

*2.3 Photovoltaic Model*

PV array consists of multiple modules in parallel and series combination. No of modules in parallel and series depends on required current and voltage of array. The voltage to current relation in PV system is non linear in nature. The output power of PV array varies due to either change in load current (or) solar radiation. For this frequency regulation study it is considered that the PV power varies only due to solar radiations. The transfer function model of PV system is show in Fig.5[20].

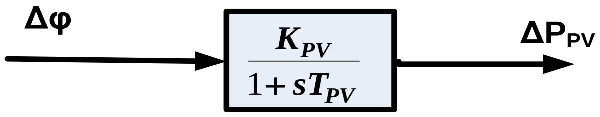



**Fig.5.** First order transfer function model of PV system

*2.4 Battery Energy Storage System (BESS)*

Conventional frequency regulation units like DEG responds slowly for frequency deviations. This DEG is associated with inertia and the direction of DEG is not easy to change when they participate in frequency regulation. Whenever sudden load change occurs in MG, frequency deviations exceed the tolerance limits because of the sluggish response of DEG. To overcome this problem and for improving dynamic response a BESS system is introduced. Transfer function model of BESS is shown in Fig. 6.

There are several advantages with BESS like fast access time and accurate control of output power. BESS will work in charging/discharging mode. If $f$ is positive then $P_{BESS}$ is negative, BESS will works in charging mode. If $f$ is negative then $P_{BESS}$ is positive, BESS will work in discharging mode.

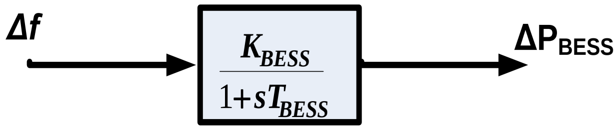



**Fig.6.** First order transfer function model of BESS

## 3. Conventional & Fuzzy PI Controller

Conventional PI/PID controllers are tuned based on predetermined operating conditions. In case, if sudden change in operating conditions these controllers fails to provide acceptable performance. Especially the autonomous MG consists of more uncertainties hence, conventional controllers fails to keep the frequency within acceptable range. If PI controller can continuously able to track the changes in operating condition, optimal control strategy is achievable.Continuous tracking of the PI controller can be achievable with fuzzy logic control (FLC).

*3.1 Fuzzy Logic Based PI Controller*

Mamdani type FLC is used to tune the PI parameters. Fuzzy logic controller is trisected as fuzzifier, inference engine and the defuzzifier. First one assigns membership ranges to two inputs and one output. Five normalized MF'S considered for each input & output, represents the fuzzy set variation from negative large to positive large having centroids at -1,-0.5,0,0.5,1 respectively[21]. The MFs maps the crisp values into fuzzy variables. Triangular MFs are used to define the degree of membership. Fig. 7 shows MFs for $\Delta f$, $\Delta f^*$ & $U_f$.

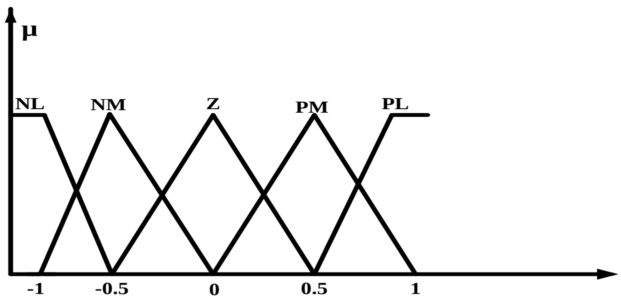



**Fig.**7. Membership functions of $\Delta f$, $\Delta f^*$ & $U_f$.

The Second section is inference engine(IE). This IE consists of data base and rule base. They contains information of control rules and linguistic labels. Decision making is inferring control action from rule base which is shown in Table 1 [22].

The third section is the Defuzzification, which converts sum of fuzzy singleton outputs into a crisp value which is the required frequency restorative control command to the governor. Eq. (4) represents equivalent crisp output [23].

**Table1.** Fuzzy logic rules

| Δf | Δf* | | | | |
|---|---|---|---|---|---|
| | **NL** | **NM** | **Z** | **PM** | **PL** |
| **NL** | NL | NL | NL | NM | Z |
| **NM** | NL | NL | NM | Z | PM |
| **Z** | NL | NM | Z | PM | PL |
| **PM** | NM | Z | PM | PL | PL |
| **PL** | Z | PM | PL | PL | PL |

$$U_f = \frac{\sum_{r=1}^{P} \varsigma_r \theta_r}{\sum_{r=1}^{P} \varsigma_r} \quad (4)$$

Where $\varsigma = [\varsigma^1, \varsigma^2, ----\varsigma^N]$ and $\varsigma_i = \frac{\varsigma_i}{\sum_{k=1}^{P} \varsigma_k}$ (5)

FLC based PI controller has superior performance while compared with PI controller. The key factor about the FLC is, its performance is highly depends on its parameters (i.e. MF's and rule base). Without precise information about the system, the MFs and the rule base cannot be selected properly. The designed FLC hence doesn't provide optimal performance over a broad range of operating conditions. To overcome this problem, an AFLC is proposed for providing optimal performance in broad range of operating conditions.

## 4. TLBO Tuned Fuzzy PI Controller

There are several approaches for tuning fuzzy parameters (either MFs or MFs scaling factors), Such as trail & error method, few Meta heuristic techniques like GA, PSO. But problem with this type of optimization techniques are their performance is highly depends on algorithm specific control parameters (for example inertia weight, cognitive & social parameters in case of PSO, parent selection, cross over & mutation in case of GA). Improper selection of these parameters may lead the solution towards divergence. To overcome this problem control parameters free optimization technique is addressed in this paper to tune the scaling factors of MF's. The detail model of proposed adaptive fuzzy logic controller is shown in Fig.8

TLBO algorithm has been introduced in 2012 by R.V.Rao et.al, inspired from teaching-learning process among students and teacher. The main advantage with TLBO is, it is free from algorithm specific parameters, and where so many algorithms inspired from social behaviour of various creatures are highly depends upon on their controlling parameters. This technique basically mimics the teaching learning ability of teacher and students in class room. This algorithm describes two modes of learning a) through teacher known as teacher phase b) through interaction of each learner with other learners known as leaner phase. Total population is considered as learners and number of subjects offered to the learners is considered as design variables and learners'

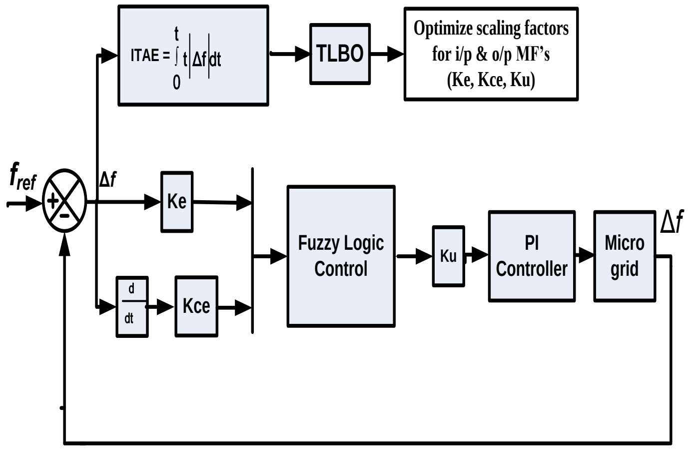



**Fig.8.** TLBO-Fuzzy based PI controller for secondary frequency control

final result is considered as fitness value of optimization problem. The best solution in population is considered as teacher. The total TLBO algorithm classified into two phase's first one is "teacher phase" and second one is "learner phase"[24].

a) Teacher Phase

In this phase teacher tries to improve the mean result of class from $a_1$ to any other value $a_2$ depending on his (or) her capability called teaching factor($T_F$).At any iteration i, let us consider 'n' number of subjects(design variables), 'p' no of learners (population size (k=1,2---p) ). $M_{n,i}$ is the mean result of learners in a particular subject 'n'(n=1,2,3--m).The best overall result $X_{total-kbest,i}$ considering all subjects together obtained in the population considered as best learner kbest. According to this algorithm the best learner is considered as teacher.

$$mean\_difference_{n,k,i} = rand()*(X_{n,kbest,i} - T_F M_{n,i}) \quad (6)$$

$X_{n,kbest,i}$ = Best learner in subject considered as teacher; rand= random number between [0-1]; $T_F$= teaching factor; this factor decides the value of mean to be changed. $T_F$ can be expressed as

$$T_F = round[1 + rand() * \{2-1\}] \quad (7)$$

$T_F$ =1 indicates no increase in knowledge level of learner in a particular subject 'n'. $T_F$=2 indicates complete transfer of knowledge.

$$X'_{n,k,i} = X_{n,k,i} + Mean\_difference_{n,k,i} \quad (8)$$

$X'$ is the updated value at the end of teacher phase and it is accepted if it gives better fitness value. This updated value is considered as input to learner phase.

b)Learners Phase

Second phase in this algorithm is learner phase. In this phase learners improve their knowledge by interacting among themselves. Select two learners in the population A &

B randomly such that $X'_{total\_A,i} \neq X'_{total\_B,i}$. Eq.(9)&(10) describes how learners transfer their knowledge each other.

$$X''_{n,A,i} = X_{n,A,i} + r_i (X'_{n,A,i} - X'_{n,B,i}) \text{ if } X'_{n,B,i} < X'_{n,A,i} \quad (9)$$

$$X''_{n,B,i} = X_{n,B,i} + r_i (X'_{n,B,i} - X'_{n,A,i}) \text{ if } X'_{n,A,i} < X'_{n,B,i} \quad (10)$$

following steps summarizes how FLC MF's scaling factors are tuned using TLBO technique.

Step1: Initialize the population using $X_n = lb + rand*(ub - lb)$

where lb=[0.1 0.1 0.1]; ub=[1 1 1].

Step2: Calculate fitness of each learner using following fitness function min [ $\int_0^t t|\Delta F|dt$ ].

Step 3:In the population best fitness is considered as teacher calculate the mean result of learners in each subject (variable).Calculate mean_difference & $T_F$ using Eq.(6)&(7).

Step 4:Update each learner's knowledge with the help of teachers knowledge using Eq.(8) .

Step 5:Each learner improves his/her knowledge by interacting with each other according to Eq.(9) or Eq.(10).

Step 6: If termination criteria met stop; display optimal scaling factors else return to step 2.
Various parameters of two algorithms are presented in Table 2. The computational flow chart for online TLBO based fuzzy PI controller design approach is shown in Fig.9

**Table 2.** Controlling Parameters

| Algorithm | Algorithm specific Parameter values | Common controlling parameters |
|---|---|---|
| PSO | Inertia weight w=0.65<br>Cognitive parameter $c_1$=2<br>Social parameter $c_2$=1.5 | No of iterations=50<br>Population size=20<br>No of variables=3 |
| TLBO | Not Applicable | |

## 5. Results & Discussion

In order to verify the robustness of proposed AFLC, time-domain simulations are perfomed by using MATLAB software. A comparative study among four controllers i.e. TLBO tuned fuzzy logic controller, PSO tuned FLC, FLC and PI controller are carried out in presence of $\Delta P_L$, $\Delta P_{WP}$, $\Delta P_\varphi$ as disturbances. To study the superiority of the proposed controller, four critical scenarios are considered.

Scenario 1 [Load Fluctuation $\Delta P_L$]: Fig. 10 (a) shows a multiple step load deviations at 2, 50, 100, 150, 200, 250, 300 & 350 seconds respectively Corresponding MG frequency response is shown in Fig. 10 (b) .

Scenario 2 [Wind power fluctuations $\Delta P_{WP}$]: Highly fluctuating wind power is considered as shown in Fig. 11 (a) for testing effectiveness of proposed controller. Corresponding MG frequency response is shown in Fig. 11 (b).

Scenario3 [Solar radiation changes $\Delta P_\varphi$]: A multiple step changes in solar radiation at 2,50,100,150,200,250,300,350 seconds respectively as shown in Fig.12 (a) & Fig.12 (b) shows the Corresponding MG frequency deviations.

Scenario 4 [Simultaneous changes in $\Delta P_L$, $\Delta P_{WP}$, $\Delta P_\varphi$]: Multiple disturbances are considered simultaneously as shown in Fig.13 (a) & Fig.13 (b) shows the Corresponding MG frequency deviations.

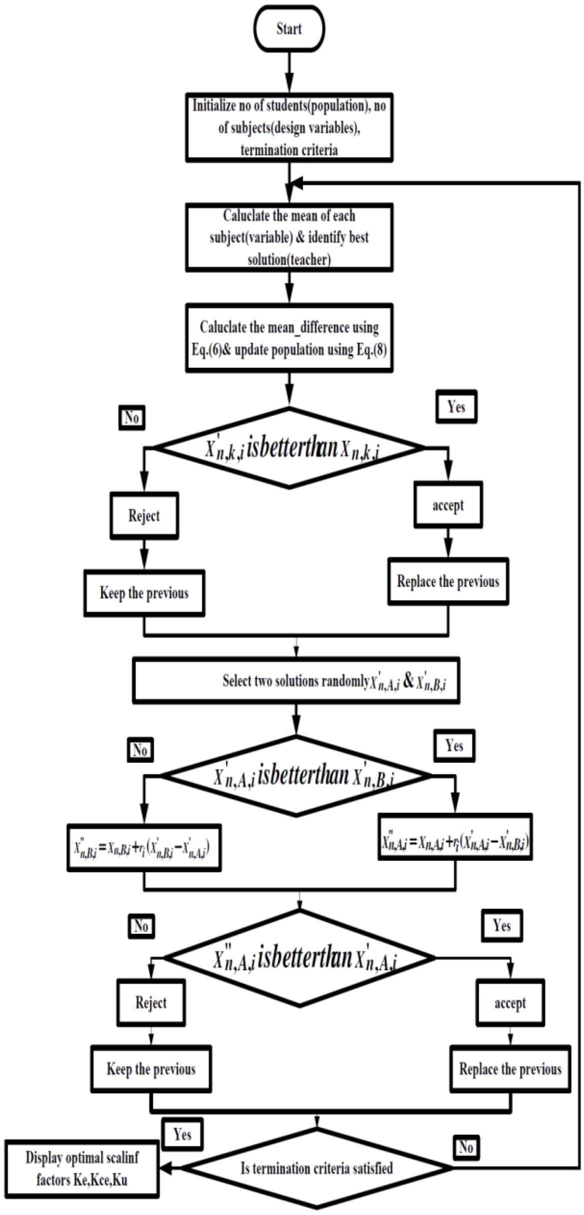
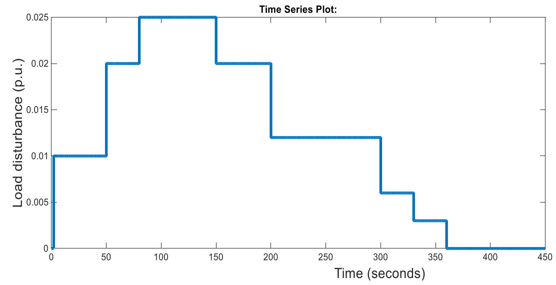
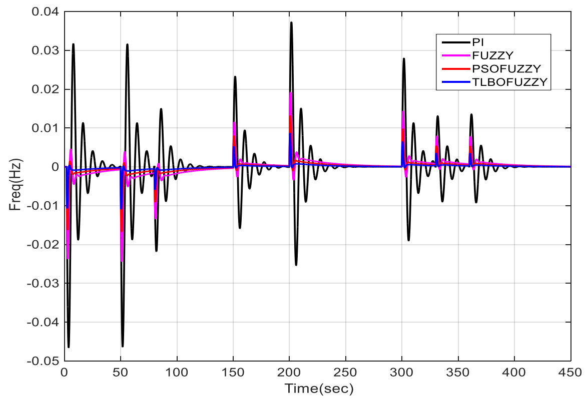



**Fig. 9.** Flow chart for online TLBO -Fuzzy design

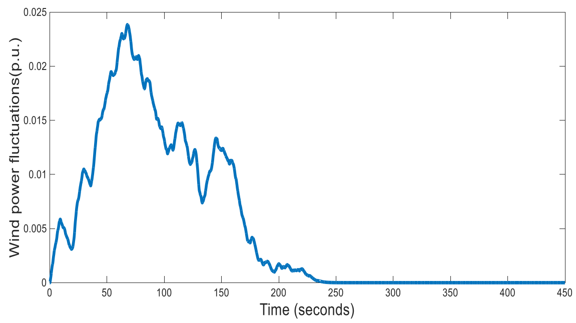



(a)

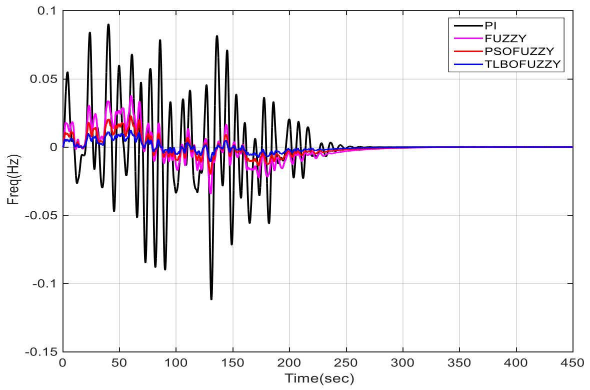



(b)

**Fig.10.** (a) Load fluctuations b) MG frequency deviations

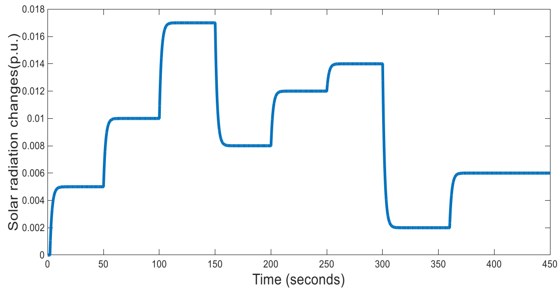



(a)




(b)

**Fig.11.** (a) Wind power fluctuations b) MG frequency deviations




(a)

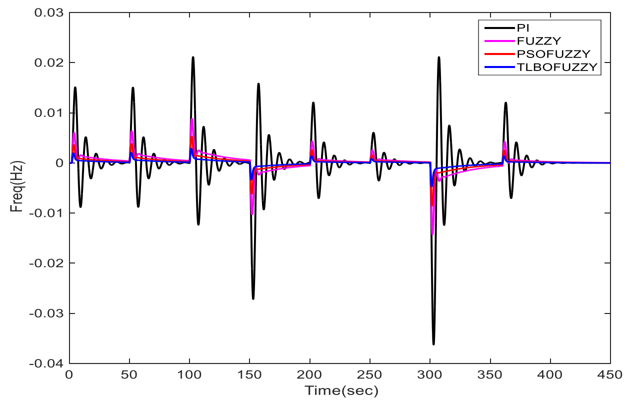
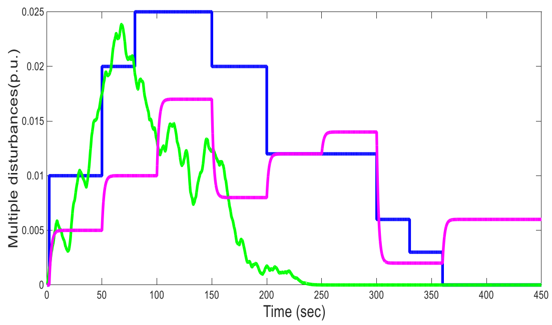
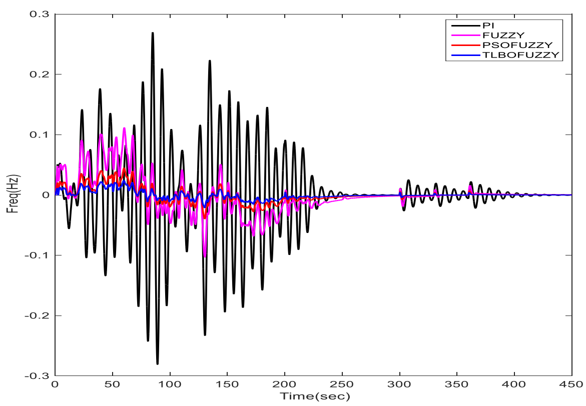



**Fig.12.** (a) Solar radiation changes b) MG frequency deviations




(a)




(b)

**Fig.13.** (a) Multiple disturbance b)MG frequency deviations

The performance index ($\int_0^t t|\Delta F|dt$)for four scenarios tabulated and given in Table 4, Scaling factors for scenario 4 shown in Table 3.

**Table 3.** I/P & O/P MFs scaling factors

| SCALING FACTORS | FUZZY | PSO-FUZZY | TLBO-FUZZY |
|---|---|---|---|
| $K_e$ | 0.5 | 0.3069 | 0.1644 |
| $K_{ce}$ | 0.5 | 0.2909 | 0.3216 |
| $K_u$ | 0.5 | 0.2817 | 0.1934 |

**Table 4.** Performance index for different scenarios

| SCENARIO | PI | FUZZY | PSO-FUZZY | TLBO-FUZZY |
|---|---|---|---|---|
| SCENARIO 1 | 0.00751 | 0.000384 | 0.000329 | 0.000296 |
| SCENARIO 2 | 0.00653 | 0.000964 | 0.000651 | 0.000478 |
| SCENARIO 3 | 0.00432 | 0.000588 | 0.000423 | 0.0001609 |
| SCENARIO 4 | 0.00956 | 0.0009978 | 0.0007654 | 0.0005662 |

From the four scenarios, simulation results shows that proposed TLBO tuned fuzzy controller is providing better performance than PSO tuned FLC and also with the conventional FLC. Diversity in load, highly uncertainty in renewable generation and complexity in functionality makes frequency control of autonomous MG is more complex in nature. As shown in the results, conventional controller fails to meet frequency limitations. From the above results it is evident that the robust frequency controller like proposed adaptive fuzzy logic controller may be an inevitable solution for MGs and it may be also suitable for modern power grids.Fig.14 shows the performance index for TLBO-Fuzzy & PSO-Fuzzy.

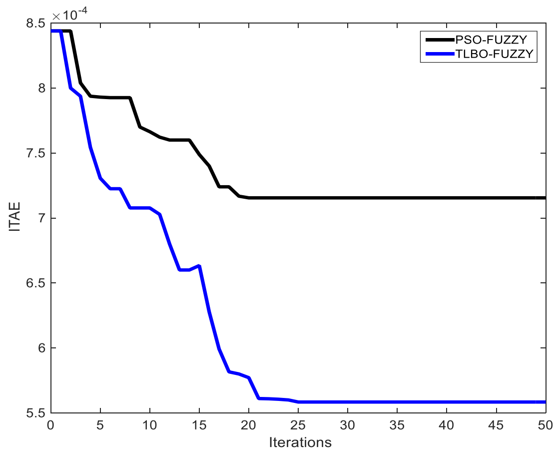



**Fig. 14.** Convergence characteristics

## 6. Conclusion

In this paper, TLBO tuned FLC is proposed for frequency regulation problem in an autonomous MG with the presence of multiple disturbances. From simulation results it is clear that conventional integral controller fails to provide better performance in the presence of multiple disturbances. Considering this as a problem, TLBO tuned FLC is used to control the frequency fluctuations of MG. This controller tunes the MF's scaling factors according to operating condition which improves the performance of FLC as its performance highly depends on its parameters. Four scenarios confirm the superiority of the proposed controller when compared with the other three controllers. The simulation studies finally concludes that the proposed TLBO tuned FLC will improve the frequency regulation of MG With minimum frequency fluctuations and can be implemented for real-time control of MGs.

## Appendix

The parameter values of Autonomous MG (Fig.1) is shown in Table.A1

**Table A1.** Parameter values of autonomous MG

| PARAMETER | VALUE | PARAMETER | VALUE |
|---|---|---|---|
| M | 0.1667 | $T_2$(S) | 2 |
| D | 0.015 | $T_3$(S) | 3 |
| $K_{BESS}$ | 1.5 | $T_{BESS}$(S) | 0.1 |
| $K_{PV}$ | 1 | $T_{FC}$(S) | 4 |
| $K_{WTG}$ | 1 | $T_{PV}$(S) | 1.5 |
| $T_1$(s) | 0.025 | $T_{WTG}$(S) | 2 |

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