Frequency Management Strategies for Local Power Generation Network

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Abstract**—**This paper presents an intelligent load frequency control technique based on ANFIS controller which is capable to restore system frequency within small fraction of time. Frequency deviations in microgrid occur when the system supply is not sufficient to match the demand. Efforts are required to keep the frequency deviation within acceptable limit. Using vehicle-to-grid technology, where electric vehicles are used as energy storage elements for load frequency control in microgrid. For generating the control action to electric vehicles and energy sources in microgrid, type-2 ANFIS has been employed for quick frequency stabilization in the presence of load and source disturbances. Diesel generator and wind generator are DG sources considered in this paper and electric vehicles are used as energy storage element. Optimal power sharing among the different generating units and electric vehicles is achieved by ANFIS controller. Adaptive nature of ANFIS makes it more suitable and highly robust controller for a complex inter-connected system. Simulation results demonstrate that ANFIS controller is highly efficient as compared to PID controller, fuzzy logic controller, and interval type-2 fuzzy logic controller.

Keywords*-Load frequency control; Microgrid; Electric vehicle; ANFIS*

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I. INTRODUCTION

Power structure development is essential with the growing demand [40, 51]. Microgrid has taken the place of an indispensable segment in the conventional power system to support its capability. A microgrid economically generates power for its local load by locally available energy resources [1]. Microgrid secures supply to critical loads and supports the main grid during load variations [41-46, 48, 50, 52]. Microgrid is able to supply its load even when the main grid fails to do so, either due to fault or weather caused problems and remove the power quality and reliability issues [47, 49, 53, 56]. There are two modes of operation of microgrid: grid-connected mode and standalone (islanded) mode. It can be isolated from the main service grid with almost negligible interruption to the loads connected to microgrid. This is known as islanded mode of operation of microgrid. In grid-connected mode, microgrid shares the peak demand during peak load period and prevents utility grid failure.

Microgrid has renewable energy sources as its primary source of electricity generation. Since, almost all renewable sources like solar energy, tidal energy and wind energy, etc. are intermittent in nature; the distributed generation in microgrid has to generate power from intermittent energy available for power generation as well as variable demand. Consequently, there is mismatch between supply and demand which induces frequency and voltage deviations in microgrid. Frequency and voltage fluctuation cause severe damage to the connected load as well as system infrastructure. These problems are more dominating when microgrid is operating in islanded mode. On the other hand, when microgrid is connected to main grid, the power balance is easily maintained in such a way that if generated power increases more than the energy demand the surplus power is transferred to the main grid and vice-versa. Thus, the system frequency is maintained within prescribed bounds. Therefore, only islanded mode demands a robust load frequency control (LFC) strategy for balancing the active power supply between distributed generation units of the microgrid and stabilizing the frequency and voltage within acceptable limits of the system [2].

To meet the desired control number of storage units such as a large battery energy storage unit (BESS), pond storage, flywheel etc. are required. BESS is used in different configuration of interconnected system for load frequency control [3] [4]. Battery storage units supply deficit amount of power and operate in discharging mode during high load period and operate in charging mode during low load hours. Although, their quick response and control make them the best possible solution for frequency control [55] but due to their high cost and maintenance, they impose a huge burden on microgrid owner. Electric vehicles (EVs) seem to be the great substitute for BESS as they promote energy saving and are also environmentally friendly [5, 6]. Private electric vehicles remain idle in parking stations for almost entire (95% time of the day) day. In this duration, these EVs can be used for frequency correction in isolated microgrid. EVs can exchange power in either direction, that is to say that EV during charging act like a load to the grid and consume electric energy [7], while a charged EV is considered as a source and supplies required power to the grid [8]. Thus, a fleet of EVs is used as virtual BESS based on vehicle-to-grid technology. Many researchers have utilized vehicle-to-grid technology for realizing LFC mechanism in microgrid [3-6, 9].

The load frequency controller manages real power variations in the system to maintain the frequency within desirable limits and enhances the system performance [9] [10]. A proper control over frequency increases energy efficiency, reliability, quality of power, reduces the need of protective devices and hence reduces the maintenance cost. Various conventional controllers for LFC have been suggested in the literature such as PI, PID controllers. However, conventional controllers cannot handle the uncertainties of complex power system network. Therefore, some intelligent controllers have also

ISSN: 2454-4248
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been utilized for LFC, for instance, fuzzy logic based, artificial neural network based and adaptive neuro fuzzy inference system based controllers. Beside these controllers, hybrid controllers like fuzzy-PID have also drawn the attention of many researchers [11] [12]. Among different controllers, fuzzy logic based controllers are capable of delivering the desired performance and taking care of maximum uncertainty in the system parameters.

Owing to their reliability [54], simplicity and robustness, fuzzy logic technique has been relied upon for LFC in numerous research work [5, 11, 12, 15, 19, 22, 28, 29, 30]. But, these works incorporate type-1 fuzzy sets (T1 FS) which cannot handle all rule uncertainties through their membership functions (MFs) [13-17]. Therefore, this work uses type-2 (T2) fuzzy logic which is an extension of T1 fuzzy logic proposed by Zadeh. More particularly, interval T2 fuzzy logic has been used here. More uncertainties as compared to T1 FS can be handled through general T2 fuzzy sets [18, 19]. Merging the advantages of T2-fuzzy logic with that of artificial neural networks, this work presents LFC with adaptive neuro fuzzy inference system (ANFIS) which handles complex and nonlinear systems in a more robust way.

This work deals with the frequency deviations occurring on account of disturbances in load demand and energy sources [60-65]. A diesel generator and a wind generator are considered as DG units in microgrid, while electric vehicles are used as energy storage units. The diesel generator is taken as variable power source whose power output can be varied by the controller action; whereas wind power is considered as constant power supply. The frequency deviations originated due to sudden variations in load and wind power supply, have been controlled using EVs with vehicle-to-grid technology. Type-2 ANFIS has been proposed for generating the control action for LFC in microgrid. The control action of ANFIS has been validated in case of load fluctuations and source disturbances. Superiority of the ANFIS controller over PID controller, fuzzy-PID controller together with interval T2 based fuzzy-PI controller is verified through simulation results in MATLAB/Simulink.

The results in terms of settling time, peak overshot and peak overshoot clearly show the potency of the proposed controller in stabilizing the frequency deviations

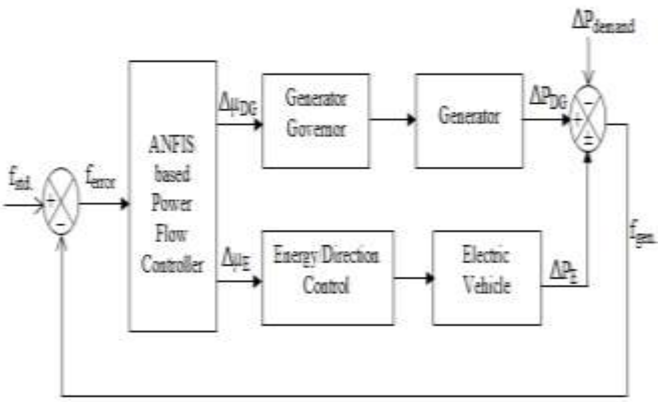

Figure 1. Block Diagram of the Proposed Methodology

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II. Load Frequency Control Model For Islanded Microgrid

This paper proposes vehicle-to-grid technology for LFC using ANFIS as the controller. An ANFIS based controller utilizes the combined advantages of artificial neural network and fuzzy logic [27]. The proposed LFC model is shown in Fig.1. The model consists of diesel generator, electric vehicle and ANFIS controller. The ANFIS controller generates the active power sharing signal for all active elements of microgrid by identifying the frequency error(f_{error}).

Frequency error signal, f_{error}, is the difference between microgrid instantaneous frequency, f_{gen} and microgrid desired frequency, f_{std}. The error frequency signal is fed to ANFIS controller to generate command signals, i.e., $\Delta\mu_E$ and $\Delta\mu_{DG}$ for electric vehicle and diesel generator respectively. $\Delta\mu_E$ decides the charging/discharging mode of electric vehicle or in other words, decides the direction of power flow between electric vehicle and microgrid. $\Delta\mu_{DG}$ controls the governor action to adjust the generated power from generator. When there is variation in power demand, ΔP_{demand}, frequency deviations occur which make generated system frequency, f_{gen} different from standard system frequency, f_{std}. The frequency difference is converted into suitable command actions by ANFIS based power flow controller for LFC of microgrid. The individual components of the proposed methodology have been modeled in MATLAB/Simulink. Different components of proposed system are briefed in the following sub-sections.

A. *Electric Vehicles*

There is different number of EVs in each charging station, so an equivalent model for a single charging station parameterizing all of its EVs is considered here. An inverter which is capable to handle the power flow in either direction is then connected to the equivalent model. Fig. 2 shows an equivalent circuit model of EVs charging station used for LFC [29].

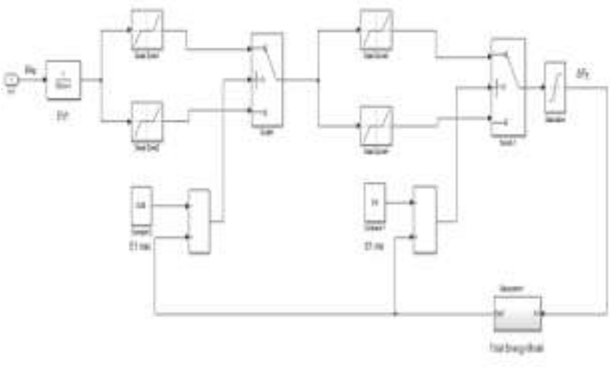

Figure 2. Model of Electric Vehicle

This model is used to calculate the total charging and discharging power in controllable state. In Fig. 2, the time constant of EV is denoted by T_e and $\Delta\mu_E$ represents EV's LFC correction signal. E is the instantaneous level of energy at the instant of use of the EVs. E_{min} and E_{max} denote the minimum and maximum bounds of usable energy respectively. ΔP_E shows the discharging/charging power [9]. When $\Delta P_E = 0$, transfer of energy is zero, in other words, it shows the idle mode of EV. When $\Delta P_E > 0$, the EV is discharging (supplying power to grid) and when $\Delta P_E < 0$, the EV is charging (absorbing excessive power from grid). $-\mu_E$ and $+\mu_E$ represent EV's discharging and charging limits respectively. It may be noted that the EV only discharges in range of $(0-\mu_E)$ if the stored EV energy overreaches the upper limit, E_{max}, considered as reference. Similarly, if $(-\mu_E - 0)$ is the range of EV, the stored energy is lesser than the lower limit, E_{min}[30], it only charges within this range.

B. *Diesel generator*

The superiority of small diesel generator (DG) is its ability to automatically adjust its output by regulating the fuel supply adaptively within certain limits. DG has low starting time, high durability, high efficiency and can run continuously if required [31]. DG automatically adjusts its output power with variation in demand. Continuous time transfer function for DG is considered in this work. This model comprises a speed governor with generator. In Fig. 3, Δf shows frequency deviation and $\Delta\mu_{DG}$ is the LFC signal transmitted to DG. T_g and T_d are governor and DG time constants respectively. R is the DG speed regulation coefficient, $\pm\delta_{DG}$ denotes range of power ramp rate and ΔP_{DG} denotes output power increment.

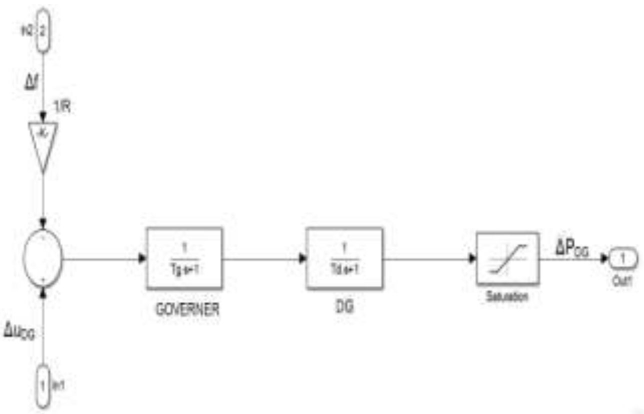

Figure 3. Diesel Generator Model

Zero value of ΔP_{DG} represents the minimum level of DG power and it is just enough to balance the microgrid generation and consumption. So, there is no frequency variation, i.e., the error signal is zero $\Delta f = 0$. $\Delta P_{DG} > 0$ is an indication of higher generation than demand and vice-versa.

C. *Complete Simulation Model*

Overall microgrid scheme with EV and proposed ANFIS controller is shown in Figure 4. The complete model is having one DG, two modeled electric vehicles (EV1, EV2) and power disturbances produced by unequal generation and demand, i.e., ΔP_D. Variations in ΔP_D are either due to load fluctuation, ΔP_L or wind power generation fluctuation, ΔP_W. Both cases are considered together also. Wind power fluctuation (ΔP_W) is taken as step input source. Different parameters used in simulation are given in Table 3 [32-34]. Here, H_t denotes the equivalent inertia of grid [32].

TABLE I. MICROGRID PARAMETERS

Grid Parameters	Symbols	Values
Diesel generator	T_g	0.1 sec
	T_d	8 sec
	δ_{dg}	0.001 pu MW/sec
	R	2.5 Hz/pu/MW
Electric vehicle 1	T_{e1}	1 sec
	δ_{e1}	0.01 pu MW/sec
	μ_{e1}	0.025 pu MW
	E_{max} & E_{min}	0.95 & 0.8 pu MWh
Electric vehicle 2	T_{e2}	1 sec
	δ_{e2}	0.01 pu MW/sec
	μ_{e2}	0.016 pu MW
	E_{max} & E_{min}	0.9 & 0.8 pu MWh
Inertia of grid	H_t	7.11 sec

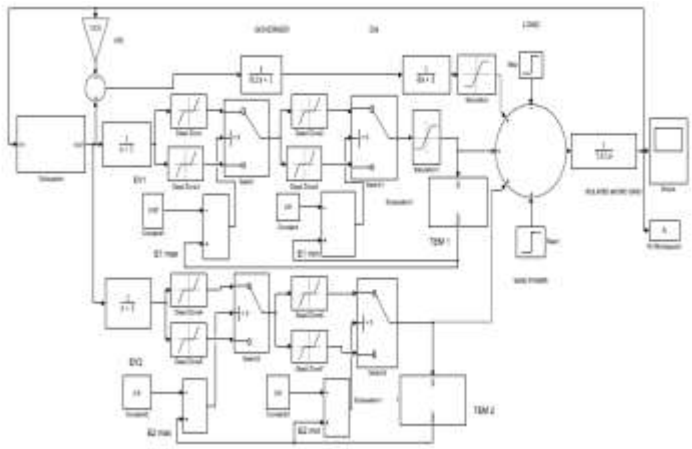

Figure 4. Complete ModeloOf Microgrid Including EV and ANFIS

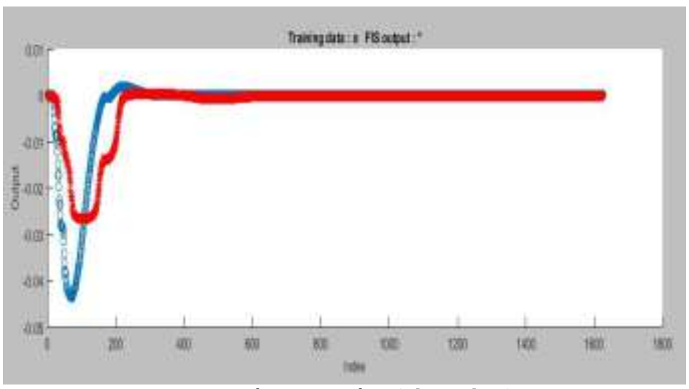

Figure 5. Output of ANFIS Before (Blue Colour) and After Training (Red Colour)

D. *ANFIS Controller*

Sugeno-type ANFIS is designed as the power flow controller. ANFIS generates the best FIS for LFC [28]. ANFIS uses "gbell" type membership function. The designing of ANFIS controller starts from PID controller for training data collection by simulating the designed model and with interval type-2 fuzzy logic controller in MATLAB/Simulink. Then, training data is loaded and optimized FIS is generated. Fig.4 shows the output of ANFIS before (blue colour) and after training (red colour). As it is apparent from Fig.4, there is low undershoot in ANFIS output after training. Therefore, trained ANFIS generates fast and accurate command signal corresponding to frequency deviation of the system.

E. Type-2 ANFIS Controller

ANFIS, i.e., acronym for adaptive neuro-fuzzy inference systems, was proposed by Jang in 1997. ANFIS is an adaptive system incorporating the benefits of both neural networks and fuzzy logic. Fuzzy logic enables us to work in uncertain and ambiguous situations. But, fuzzy logic gives the random output depending on random membership functions and random rule base. To prevent from the random output, the principle of artificial neural networks is embedded in fuzzy logic. This fusion introduces the adaptive capabilities in fuzzy logic. In ANFIS, suitable rule base and membership functions are selected using neural network's back-propagation algorithm according to the concerned application. Thus, ANFIS is a fuzzy inference system which facilitates the tuning of parameters of membership functions using back-propagation algorithm or any least-square based algorithms. In this way, fuzzy system learns from the data on which it is to be applied.

TABLE II. INTERVAL TYPE-2 FUZZY LOGIC RULE BASE

e	de/dt					
	PS	PM	PL	NL	NM	NS
S	PS	PS	PM	NL	NM	NS
M	PS	PM	PM	NL	NL	NM
L	PM	PM	PM	NL	NL	NL

In ANFIS architecture, two inputs are chosen, i.e., error signal, e and rate of change of error signal, $^{de}/_{dt}$. For input and output variables, the membership functions are selected as triangular one corresponding universe of discourse range is selected between [-1, 1]. Originally, ANFIS was proposed with type-1 (T1) fuzzy systems. But T1 fuzzy logic system faces many problems in handling uncertain and complex systems. So, to overcome these problems, T2 fuzzy logic system has been used in ANFIS in this work [18] [19]. T2 fuzzy sets are identified by its membership functions. The fuzzy logic system which comprises at least one T2 fuzzy set comes into the category of T2 fuzzy logic system. Most widely used, interval T2 (IT2) fuzzy set is a special case of T2 FS having low computational cost [26]. IT2 fuzzy sets are bounded by lower membership function (LMF) and upper membership function (UMF). In this work, ANFIS has been trained using the data collected from IT2 fuzzy logic system. For IT2 fuzzy logic system, the rule base having 9 rules as shown in Table 2, has been used. For input and output variables, six triangular membership functions are selected. After training, ANFIS has been utilized for LFC with gbell membership function for optimized results.

III. RESULTS

An overall microgrid scheme including electric vehicle, diesel generator and ANFIS controller has been modeled in MATLAB/Simulink. The designed model has also been simulated using different controllers like PID controller, fuzzy logic controller and interval T2 fuzzy logic controller. Obtained results are compared to validate the efficacy of the proposed controller, i.e., ANFIS under two different cases of the load variation. In first case, simulation is carried out for step load disturbance of 0.05 pu at time t = 50 sec. In second case, source (wind power) fluctuation of 0.02 pu is also considered at time t = 30 sec along with step load disturbance of 0.05 pu at time t = 50 sec.

Fig. 7 and Fig. 8 show the resultant frequency deviation plots of the microgrid with load fluctuation only and load fluctuation with source fluctuation respectively. The proposed controller exhibits better frequency stabilization with a significantly low peak overshoot and quick damping of the frequency deviations. Outperformance of the proposed ANFIS controller in controlling the frequency deviations in microgrid is apparent from Fig. 7 and Fig. 8. It is observed from Fig. 7 that conventional PID shows the worst performance in frequency stabilization. FLC performs better than PID but slightly lags behind IT2FLC in terms of all the parameters, i.e., settling time, peak overshoot and peak undershoot. ANFIS performs better than all these controllers having good values of all the parameters as listed in Table 4. Similar performance is observed in second case, i.e., load fluctuations with source fluctuations. ANFIS has the best performance as compared to PID, FLC and IT2FLC.

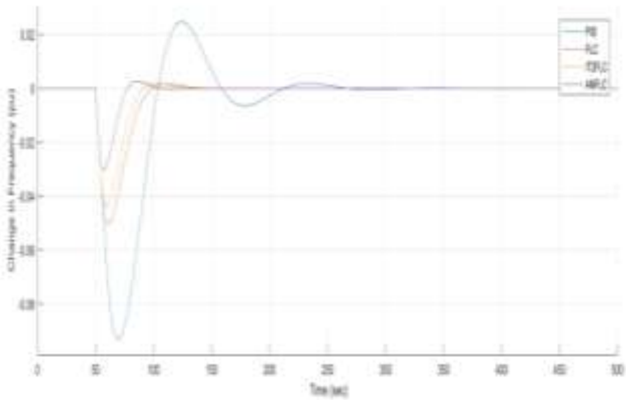

Figure 6. Frequency Deviation of the Microgrid with Load Fluctuations

Table 4 shows the comparative analysis of settling time, peak overshoot and peak undershoot of different controllers in case of load fluctuations only. Table 5 shows the comparative analysis of different controllers in case of load fluctuations with source fluctuations. Settling time, peak overshoot and peak undershoot is minimum in case of ANFIS in both the cases. Thus, ANFIS quickly stabilizes the frequency deviations generated due to power unbalance in the system on account of load and source fluctuations.

If the performance of ANFIS is compared in two cases, then ANFIS gives better results in case of load fluctuations only. In case of load fluctuation with source fluctuation, ANFIS takes more settling time for frequency stabilization. Moreover, peak overshoot and undershoot are also lesser in case of only load fluctuations. Thus, the results prove that the proposed controller better as compared to other controllers for LFC in microgrid using vehicle-to-grid technology.

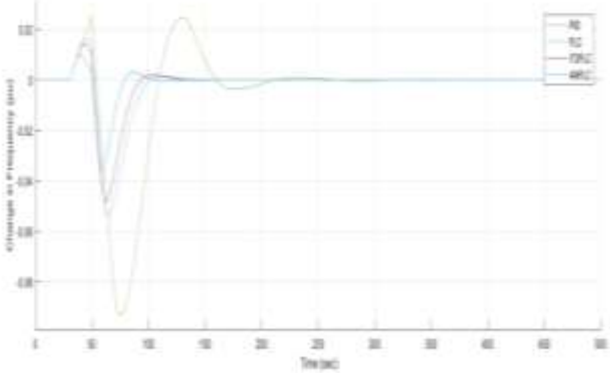

Figure 7. Frequency Deviation of the Microgrid with Wind Power and Load Fluctuations

TABLE III. COMPARISON OF RESULTS IN CASE OF LOAD FLUCTUATIONS

Controller	Settling time (in sec)	Overshoot (in pu)	Undershoot (in pu)
PID	210	0.030	-0.099
FLC	90	0.0042	-0.0528
IT2FLC	75	0.0042	-0.0459
ANFLC	**55**	**0.0041**	**-0.0317**

TABLE IV. COMPARISON OF RESULTS IN CASE OF LOAD FLUCTUATIONS WITH WIND POWER FLUCTUATIONS

Controller	Settling time (in sec)	Overshoot (in pu)	Undershoot (in pu)
PID	230	0.031	-0.099
FLC	110	0.020	-0.057
IT2FLC	95	0.017	-0.051
ANFLC	**75**	**0.0122**	**-0.0381**

IV. CONCLUSION

Due to discontinuous nature of renewable energy sources of microgrid, frequency deviation on account of load disturbances has become a major issue during islanded mode. Sudden source disturbances further augment the issue of frequency stabilization. This paper proposes load frequency control strategy with the help of an intelligent adaptive neuro-fuzzy controller in islanded microgrid. The proposed controller, ANFIS based on interval T2 fuzzy logic, is capable to reduce the effects of power fluctuations either due to renewable sources or load disturbances by quick shifting the operating point of DGs and electric vehicles. The controller is capable to efficiently synchronize the output of DGs and EVs in an optimized way. The proposed controller can also be used for multiple distributed generation sources like wind, solar and small hydro plant in coordination. By selecting the desired bounds for deviations, power sharing between all distributed generating resources corresponding to their maximum power ratings can be implemented through the proposed controller.

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