Frequency Control of Microgrid under Islanded Condition Using Fuzzy-PI based Controller

A Dissertation submitted in fulfillment of the requirements for the Degree
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Submitted by

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DECLARATION

I hereby declare that the work which I have presented in dissertation entitled, "*Frequency Control of Microgrid under Islanded condition using Fuzzy-PI based Controller*", in fulfillment of the requirements for the award of degree of Master in Engineering in Power Electronics and Drives, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is an authentic record of my own work carried under the supervision of Mr. Jitender Kaushal and Dr. Prasenjit Basak. It refers to other researcher's work which is duly listed in reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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Place: PATIALA

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It is certified that the above statement made by student is correct to the best of my knowledge and belief.

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CERTIFICATE

Certify that the dissertation entitled, "Frequency Control of Microgrid under Islanded condition using Fuzzy-PI based Controller", which is being submitted by Jashandeep Kaur in fulfillment of the requirements for the award of the Master of Engineering in Power Electronics and Drives, to Thapar University, Patiala, is a bonafide record of the candidate's own work carried out by her under our supervision and guidance. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other university or institute for award of any degree.

Place: Thapar University

Date: 26th July, 2017

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ABSTRACT

With increasing power demand, the pressure on conventional sources of energy has increased leading to depletion of fossil fuels. Burning of fossil fuels is one major factor that contributes to pollution and global warming. All these issues related with conventional sources of energy has led to a new concept of power generation which employs the use of renewable energy resources (RESs). The use of RES's lead to issue of power fluctuation in the system which further causes frequency deviations. The load frequency changes abnormally, which is fuzzy in nature, due to low system inertia and unpredictable variation in wind and solar irradiance level. The frequency fluctuation caused on account of integration of RESs is a well recognized phenomenon. To control these fluctuations storage units can be added in the system. Integration of storage units in the system also increases the reliability of the system by ensuring continuous supply of power. However, apart from integrating storage units in the system a proper control scheme can be developed for frequency control of the microgrid. In this work a fuzzy-PI based control scheme is proposed, which automatically updates the control parameters on occurrence of any disturbance in the system. A microgrid under islanded condition consisting of photovoltaic and wind generator units along with diesel generator set and storage units is considered. Further, performance of the proposed fuzzy-PI controller is verified with that of an autotuned PI controller, which is readily available in MATLAB/simulink library to get faster response. The steady state response is found minimum in case of autotuned PI controller as compared to fuzzy-PI controller.The proposed fuzzy-PI controller is validated based on ITAE (4-7%) which is higher than that attained from autotuned-PI controller. The control schemes are validated for single area hybrid microgrid and two area microgrid system. The developed model is simulated in MATLAB/Simulink environment.

Keywords: *Microgrid (MG), Distributed energy resources (DER's), PI controller, frequency control, islanded operation, autotuned-PI, fuzzy-PI.*

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LIST OF ABBREVIATIONS

MG	Microgrid
RES	Renewable Energy Resources
DER	Distributed Energy Resources
PV	Photovoltaic
DG	Distributed Generation
CHP	Combined Heat and Power
PEI	Power electronic Interfaces
PI	Proportional Integral
FLC	Fuzzy Logic Controller
VSI	Voltage Source Inverter
WTG	Wind Turbine Generator
BSS	Battery Storage System
FES	Flywheel Energy Storage
LFC	Load frequency control
MGCC	Microgrid central controller

CHAPTER 1-INTRODUCTION

1.1 MICROGRID

The depletion of fossil fuels at an alarming rate and increasing need for a highly efficient and reliable power system has made the concept of microgrid important [1]. Microgrids involve generating power from locally available resources like photovoltaic cells, wind power system, biogas, fuel cell and microturbines [2]. These sources of energy are available in abundance and are renewable in nature. The renewable sources of energy are also termed as Distributed energy resources (DERs). Microgrid (MG) is a concept that utilizes the energy generated by these DERs [3]. MGs not only help in extracting power from non-conventional resources but have also improved the power reliability and helped the concept of smart grid to emerge [4].

A microgrid can be defined as group of low voltage distribution energy resources that are connected together to feed a common load and act as single controllable unit. MGs are active distribution networks since they provide bidirectional flow of power on addition of DG units in system. A MG can be used to feed all types of loads be it residential, commercial or industrial.

MG can be classified in two categories based on nature of power being fed to the load. If the power fed to load is alternating in nature it is termed as AC microgrid, if power fed to load is DC it is termed as DC microgrid. DC microgrids have an advantage over AC microgrid since there is no issue of synchronization, voltage and frequency fluctuation. But since most of the loads are AC in nature so AC microgrids are commonly used. A typical layout of an AC MG is presented in Fig. 1.1. It consists of a PV based generating unit along with battery and flywheel storage units. Control is provided using microsource controller (MC) and load controller (LC). Microsource controller is used to control the flow of power and voltage at load end on occurrence of any fault. The load controller (LC) monitors the power flow to load based on generation and demand. When the generation is more than demand then the microgrid will supply power to all the loads. But when generation from distributed energy resources is low then the load controller will regulate power flow based on priority, the less critical loads will be disconnected and power is supplied only to the important loads.

The main advantages offered by a MG are [5]:

1. They can be installed in geographically isolated areas, since power can be produced from locally available sources of energy.

2. The distribution generation units are placed close to load so it reduces transmission and distribution losses.

3. DER's are clean sources of energy as there is little emission associated with them.

4. MG plays an important role in increasing power reliability.

5. MGs provide better scope of CHP operations.

6. Load on utility grid is reduced.

7. Improve system reliability in event of black out.

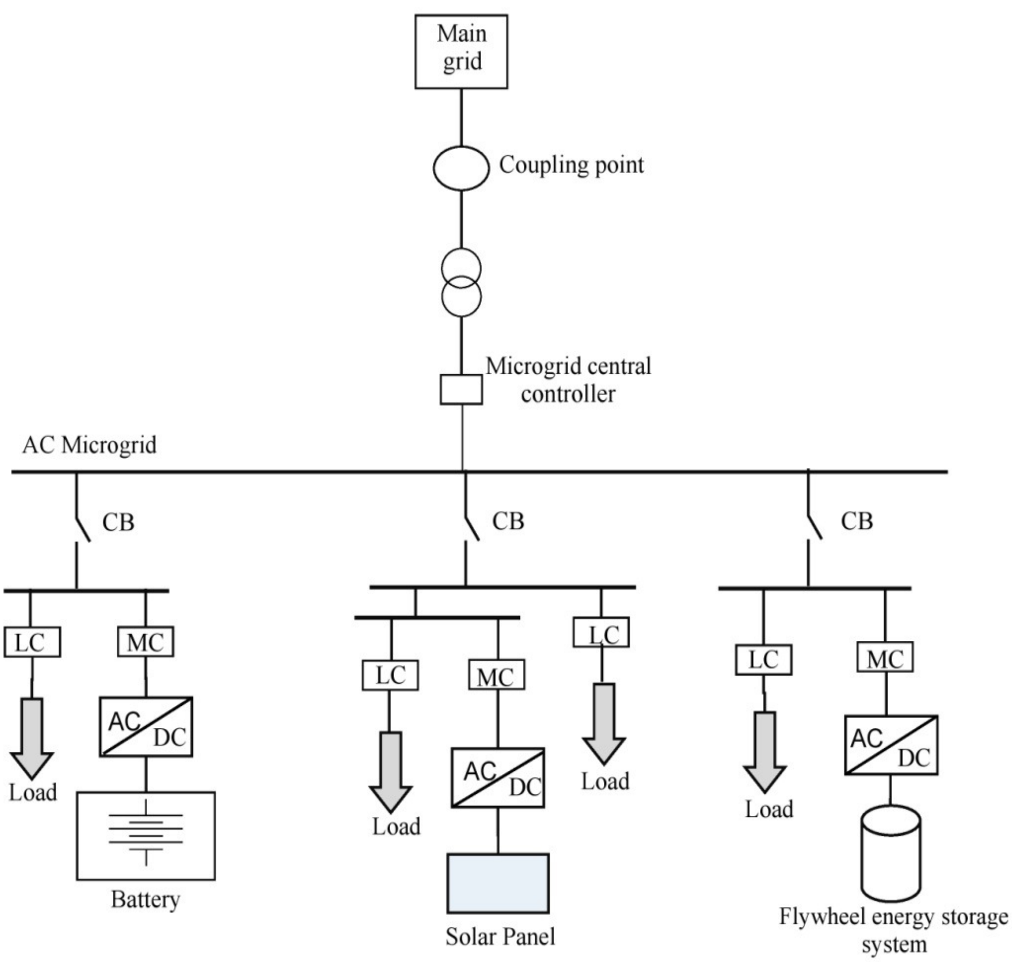


Fig. 1.1.Layout of typical AC microgrid

DERs offer a great advantage over conventional energy resources. Firstly, they are available in abundance in nature. Secondly, CO_2 emission associated with these resources is negligibly small [6]. In order to maintain power quality and proper operation of system a good control scheme and power electronic interfaces (PEIs) should be employed along with microsources [7]. Although there are numerous advantages offered by microsources; there are also few disadvantages associated with them. If we consider a PV system and wind energy system, which harness power by virtue of solar radiation and blowing winds respectively. In such systems the power generation completely depends on the environmental conditions. So the unpredictable and irregular nature of these resources poses a problem of irregular power supply, poor reliability and low efficiency. Therefore, it is important to incorporate storage units in the system in order to ensure a continuous supply of power to load and increase system reliability [8].Some commonly used storage units include battery storage system, flywheel, and super capacitors. MGs offer same operation as offered by utility system. But there are few differences between the two systems as listed below [9]:

i. Generating capacity of microsources in MG is much smaller as compared to large generators in utility system.
ii. Power generated by microsources is directly fed to distribution network of utility grid.
iii. Microsources are installed in proximity to customer premises so that CHP operations can be efficiently carried out, and power can be transmitted with proper voltage and frequency profile.

The MG is connected to utility grid through circuit breaker and this point is known as point of common coupling (PCC). Based on interaction with utility grid, the microgrid can be classified into two modes of operation [10].

1) Grid connected mode

2) Islanded mode.

1. Grid connected mode: MG is said to operate in grid connected mode when it is connected to utility grid via circuit breaker; the load is fed from both utility grid and microgrid. There is interaction between both utility grid and microgrid. Under this mode the control is mainly regulated by utility grid.

2. Islanded mode: MG is said to be operating in islanded mode when MG is not connected to utility grid i.e. the two units are isolated from each other. This isolation between utility grid and microgrid can occur naturally on occurrence of some fault or it may be intentionally created by opening of circuit breaker to carry out maintenance or for some other purpose. In islanded mode, the control is purely regulated by microgrid central controller (MGCC) so it is

important that it maintains the voltage and frequency within permissible limits and maintain power flow balance.

Although microgrids offer a large number of advantages there are still many barriers in development of microgrids such as [9]:

i. High installation cost of microgrids is one major disadvantage.
ii. Proper standards for addressing protection and operation related issues are not available.
iii. Regulation of energy supply prices in the period when utility grid is not available and load is supplied by MG.

1.2 LOAD FREQUENCY ISSUES IN ISLANDED MICROGRIDS

Under islanded mode, the MG is isolated from utility grid. Since the microgrid is not connected with utility grid so there is no external source of power, and the power balance between generation and demand is to be entirely regulated by microgrid. Thus maintaining a proper balance between power demand and generation is a challenging task.

When microgrid is operating in islanded mode any mismatch between power supply and demand leads to voltage and frequency fluctuations which have a severe effect on power system stability [11]. Any such deviations in microgrid system can cause damage to system like serious disturbances and power outage [12]. So it is important to ensure a proper control scheme in microgrid system.

Variation in power generation and fluctuating loads are main cause behind power mismatch in MGs incorporating DERs [13]. Since power generated by DERs depends upon environmental conditions so there power generation may vary over time, which causes imbalance. If power generation is more than demand, the frequency of system increases beyond nominal value, if power generation is less than the demand the frequency of system decreases. These deviations in value of system frequency can cause major issues related to power stability in microgrid system; and improper power supply to loads. So it is important to employ proper control schemes in microgrid system to cope up with voltage and frequency fluctuations in system and ensure a reliable and stable operation of microgrid system.

1.3 LITERATURE SURVEY

The load frequency variation in a microgrid is an important topic of discussion. A lot of researches are being done for developing control schemes to cope up with frequency deviations. Şerban *et al.* has discussed two main levels of frequency control i.e. the primary and secondary control [14].The author has stated that the primary control is the control which acts first within a fraction of few seconds. The control scheme employed here is the droop control. The secondary control begins simultaneously with primary control; since on account of primary droop control the frequency deviates so the purpose of secondary control is to restore the deviated frequency back to its nominal value. It has a time constant little more than primary control. The control scheme used for carrying out secondary control is PI control. The control methods were assessed through simulation.

The conventional droop control scheme for frequency control has been investigated by Kafle *et al.* [15]. The authors have suggested a frequency control of microgrid consisting of wind and PV system. The output voltage and current of VSI connected to DC battery are controlled by using proportional resonant voltage and current controllers. The reference signals for the controllers are generated using droop control. The reference voltage magnitude and frequency set points are generated by droop loop. So based on droop principle, the active power flow from inverter is regulated by frequency variation and the reactive power flow is regulated by voltage variation. The system frequency is maintained within permissible limits by setting droop value.

In a similar work Klem *et al.* [16] frequency control of microgrid is carried out using droop control. The frequency restoration is carried out by applying droop control on both generation side management and demand response, which enables them to share generation imbalance. This scheme is helpful in reducing frequency deviations, transient time and also in case of disturbance prevents the generators from exceeding the power ratings. The author has described how the application of droop control on load along with generating units is more effective in frequency restoration, and steady state is attained more quickly.

Rahmani *et al.* have discussed a droop control scheme which is different from the conventional droop control [17]. The frequency drop during transient time is decreased using the new controller. Also it helps to eliminate frequency deviation at steady state. The difference between conventional droop control and new control scheme is that in the new scheme term ω_o for frequency/active droop is considered to be changeable. The value can be changed to a new value ω_o^* so the frequency is changed to a new value. The value of ω_o^* is calculated by comparing the ω_o and deviation of frequency from desired value. The only drawback of the scheme is that power sharing between inverters is unequal. To overcome it the values of droop constants are adjusted.

Ota *et al.* considered a MG system available at Aichi institute in Japan for simulation purpose. For each simulation that was carried out they considered one DG unit along with one storage unit [18]. The authors have simulated the model under two conditions; in the first a wind system along with storage unit is considered and in second, PV system along with storage unit is considered. For both the cases, a comparison between different frequency control schemes is made. For wind generation system the control methods used are power demand estimation and proportion control. For PV system also the same methods are used. The simulation results depicted that in case of wind generation system the load demand estimation method generated better results and for PV system the active power control helped to eliminate frequency fluctuations.

Another popular technique for frequency control employs use of PI and PID controllers. Santosh *et al.* [19] have considered a microgrid in islanded condition consisting of WTG, DG and a fuel cell. The power output from WTG is considered to be constant and the output power variations of other sources are regulated by using PI controller. The tuning of controller is done using hit and trial method. The PI controllers are installed in conjugation with generator units so that they can maintain frequency at desired level by eliminating any mismatch between generation and load.

Working in the same direction Mallesham *et al.* [20] have also discussed a microgrid under islanding condition consisting of renewable generating units along with storage units. In their work they have used a proper tuning technique for PID controllers to keep the frequency of system within limits. The tuning of PID controller is carried out using Ziegler Nicholas criterion. Authors have described the tuning process by considering a range of K_f (frequency bias) as 0.1 to 10. For each value of K_f, in this range oscillations are considered, which occur on account of load disturbance. Considering a particular value of K_f corresponding to that value K_p, K_i and K_d are calculated. First the values of K_i and K_d are evaluated as zero and the value of K_p is calculated. Similarly, value of K_i and K_d are calculated. So for each value of K_f there is a corresponding set of values for K_P, K_i and K_d. Based on mathematical relation between performance criterion and ITSE (Integral Square time error evaluation) the best set of values for K_P, K_i and K_d is selected. The optimized controller gains are the one which corresponds to least value of ITSE. The importance of frequency bias in determining on calculation of controller gains is explained.

One more technique of controller tuning is discussed by Hari *et al.* based on biogeography optimization algorithm [21]. The biogeography based optimization (BBO) algorithm is used to calculate the controller parameters and to attain the best possible control. To test the efficiency of control scheme various disturbances in the system are considered. Authors have discussed the effect of variation of different control parameters on the system response. In the BBO algorithm habitat is analogous to solution of the problem. Suitability index variables are the set of variables which characterize the solution of problem. The quantity of suitability index variables (SIVs) in every arrangement is the issue measurement. The attainability of every arrangement is called its Habitat Suitability Index (HSI). A high HSI of a territory implies an extensive number of animal categories and a low HSI implies less number of species in the environment. The environment is altered by emigrating arrangement elements to different environments, and accepting arrangement highlights by migration from different living spaces. Natural surroundings with a high HSI have a high animal types displacement rate and low species migration rate. Based on relation between HSI and frequency deviation the values of P, I and D are calculated.

Yiwei *et al.* [22] have also proposed a technique for tuning of PI controller parameters. The technique proposed consists of a hierarchal control scheme where two controls are employed namely primary and secondary control. The primary frequency control is carried out using droop control and is applied to diesel engine (DE) and battery storage system. The primary control is used for small frequency fluctuations to incorporate large fluctuations secondary control scheme is used. The secondary frequency control is carried out by regulation method of DE along with PI controller. This two layered frequency control scheme is effective in frequency restoration and maintain balance between demand and generation.

Janani *et al.* in [23] have discussed a intelligence based control scheme for frequency control of microgrid under islanded condition. A fuzzy logic controller is designed by defining a set of rules based on the system behavior under normal condition. The error and rate of change of error are taken as input and the output regulates the fuel flow of diesel generator set. Depending upon the change in frequency the fuel flow rate varies. If the system frequency falls below the nominal value then the fuel flow increases in order to increase the power generation and the frequency gets restored.

A comparison between FLC and PID controller is discussed by Marzband *et al.* [24]. First the system is simulated using PID controller and then to apply fuzzy controller comparison between actual signal and reference signal is made to generate error signal. This signal is compared with the previous one to get rate of change of error. Seven membership functions are selected. Rule base is formulated based on behavior observed during operation of PID controller. Simulation was carried out considering different operating conditions in order to make comparison between both the control strategies. From the simulation results it is evident that fuzzy logic controller (FLC) provides better frequency stabilization than PID controller.

A relatively new technique using both fuzzy and PI controller has been studied by Bisht [25] has discussed a control scheme in which FLC is used to compute values of P and I for PI controller. First the system is studied under normal conditions so that error can be studied to help formation of rules. Based on the situation or condition, the corresponding rules are applied and the system frequency is controlled.

Keyser *et al.* [26] have discussed the process of autotuning in PID controllers and compared it with the performance of PID controllers which are tuned using computer aided tools. Authors have discussed that tuning of parameters is dependent upon two factors i.e. the overshoot and settling time. Nowadays most of the controllers employed in industries use the autotuning process in order to attain the best possible control. The control parameters are automatically calculated once the regulator is connected to plant. The effectiveness of controller is studied by considering by considering different cases of disturbance.

Application of autotuned PID controller for HVAC system has been studied by Wang *et al.* Since the other tuning methods like hit and trial or Ziegler Nicholas are time consuming and if the results attained are not satisfactory the system needs to be retuned. In the proposed scheme [27], firstly the controller model is developed by using relay feedback method which helps in identification of two points on nyquist plot. After the estimated model development the tuning of controller is done based on the phase margin and gain margin requirements of the system.

The autotuning of PID controller based on neural network (NN) technique is discussed by Alvarado *et al.* A NN based autotuned PI controller for an underwater vehicle is proposed [28]. The authors have mentioned the drawbacks associated with off line tunning techniques. One major disadvantage being that once the control parameters are set they don't get automatically updated with respect to change in operating conditions of the system. This degrades the performance of the controller. So a neural network based PI controller is developed which automatically updates the control parameters when any disturbance occurs in external conditions of the system.

Hang *et al.* have presented a comparative analysis between three autotuned PID controllers based on their performance when subjected to various disturbances such as measurement noise, change in load and change of set point. To evaluate the performance of controllers under different conditions benchmark tests are carried out using a process simulator that is based on microcontroller. The three controllers under consideration are "refined-Ziegler Nicholas autotuned PID controller, Satt control autotuner and Foxboro EXACT self tuning controller" [29].The main purpose of this work is to introduce a set of benchmark testing method to evaluate performance of autotuned controllers.

Frequency control technique for two area system has been discussed in [30] by Kolhe *et al.* The technique proposed is cascaded PD- PI controller. In the cascaded process the output of inner process is supplied to outer process. The main purpose of this process is to eliminate the effect of disturbance on outer process. The comparison of cascaded controller is made with conventional controller based on overshoot, undershoot and settling time.

El-Fergany *et al.* [31] have discussed frequency control technique for islanded two area microgrid. The tuning of PID controller is done using social-spider optimiser. The system is simulated under different conditions by considering different disturbances in the input signals of microgrid components. Authors have presented the algorithim for SSO method. It is inferred from the simulation results that this technique is effective in removing signal deviations.

El-Metwally has proposed a fuzzy based frequency control scheme for interconnected areas. As discussed by author, the fuzzy based controller improves the performance of system by minimizing the frequency deviation in system and also improves dynamic response of tie-line power flow. The results attained form the fuzzy scheme was compared with traditional PI controller and the performance of fuzzy controller is observed to be better than conventional controller [32]. The proposed scheme reduced the overshoot in the system, provided good damping and also the tie line power exchanged reduced.

Kumar *et al.* [33] have also discussed control scheme based on fuzzy system but here the fuzzy controller is used to tune the PI controller parameters. The proposed scheme is compared with fuzzy scheme and conventional PI control scheme. The adaptive fuzzy technique generated better results than fuzzy controller and integral controller.

1.4 RESEARCH GAP

From the literature survey it is evident that there is a need to investigate frequency control in islanded microgrids incorporating RESs. In [14] - [16] a conventional droop control scheme has been discussed by the authors. Although it minimizes the frequency fluctuations in the system but the settling time is large. In a similar work [17] a new droop control is discussed which is different from the traditional droop control; it offered an advantage of good frequency control but there was a problem of power sharing associated with it. Referring to disadvantages offered by droop control scheme most systems use PID or PI controllers. It is also evident from [19]-[22] that PI control scheme is being widely used and generates a better control response as compared to droop control. There are different methods available for tuning of controller parameters. In [19], hit and trial method is used for tuning the parameters. Although it helps in restoration of system frequency to its nominal value but tuning of such controllers is a tedious job and may not always generate desired results so the system may require retuning of parameters. Some other methods used for tuning controller parameters are presented in [20] - [22].As presented in [20] Ziegler Nicholas technique is used for tuning the parameters, which is easier and less time consuming. From [23] and [24] it can be inferred that fuzzy control scheme generates better response as compared to PI controllers and drop control scheme. Further in [25] a control scheme employing both fuzzy system and PI controller is used. The fuzzy system helps in automatically updating controller parameters whenever there is any change in system operating conditions. In [26]-[30] concept of autotuning of PID controllers is discussed, it is evident from studies that the autotuned PID controllers are widely used in industries and provide good control.[31]-[33] present control schemes used for two area microgrid systems. From the studies it is inferred that the control schemes used are the same as that used in single area microgrid system with only difference that in two area, tie-line power also needs to be regulated. Since the operating conditions of system may change at any point of time so there is a need of adaptive controllers which can automatically control the parameters whenever there is any disturbance in the system.

1.5 MOTIVATION AND OBJECTIVE

Referring to literature survey, it can be concluded that droop control and PI controllers are extensively used for minimizing frequency deviations in microgrids. Most of the tuning methods are time consuming and may require retuning if results are not satisfactory, thus degrading the performance of system and making it more tedious. A very less work is done where tuning of PI controller parameters is done using the autotuning concept. Tuning of PI controllers using fuzzy logic controller is also not much explored. Most systems use traditional methods for tuning PI controller parameters. In this work fuzzy-PI based control schemes is used for providing frequency control in both single and two-area microgrids under islanded condition. Further, the proposed scheme is compared with autotuned-PI controller.

1.5.1 OBJECTIVES

The objectives of this work have been listed below:

a) Developing a fuzzy-PI based frequency control scheme for microgrid integrating PV, wind and diesel generator system along with storage units.
b) To verify the proposed control scheme for single-area and two-area microgrid system.
c) Comparison of a proposed fuzzy-PI based controller with an autotuned-PI control scheme.

This work is further divided into three chapters. In chapter 2, the detailed discussion about proposed hybrid microgrid model is presented. Both single-area and two-area microgrid hybrid systems have been discussed.

Chapter 3 presents the discussion about control strategy adopted for minimizing the frequency deviation in microgrid. The control is provided by using PI controller. Fuzzy logic controller and autotunning are used to update the control parameters for PI controller.

In chapter 4, the results attained from both the control schemes are presented and a comparative analysis is done for both the schemes based on ITAE.

Chapter 5 presents the conclusion of the work done based on the results attained from control schemes.

CHAPTER 2-SYSTEM DESCRIPTION

An AC microgrid operating under islanded mode is considered. It consists of two renewable based generating units i.e. photovoltaic and wind generator system. The load frequency changes abnormally, which is fuzzy in nature, due to low system inertia and unpredictable variation in wind and solar irradiance level. So, irregular nature of generation from these units imposes a problem of poor power reliability and quality. The mismatch between demand and supply can be eliminated to some extent by incorporating a diesel generator set and storage units in the system. So, a flywheel and battery storage units are also added to the system. But a frequency controller is needed to solve the problem meeting generation and demand of an islanded microgrid system considering the fuzziness in frequency fluctuation. So a fuzzy-PI based control scheme for minimizing the frequency deviation is proposed. An autotuned-PI controller is also used for frequency regulation of system. The results of which are set as benchmark to make comparative analysis between the two controllers. In this work, a single area and two area isolated microgrid are considered. The fuzzy-PI and autotuned-PI controller response for both the microgrid configurations is studied. In two area system, the controllers along with frequency control, tie-line power is also regulated.

2.1 PHOTOVOLTAIC SYSTEM

Photovoltaic is a specialized term for sun oriented vitality. PV cells are generally made of silicon, material that discharges electrons when presented to light. The principle used for converting sunlight to electricity is very similar to that used for transistors and diodes. At absolute zero temperature, silicon behaves like an insulator. When solar cells is exposed to sunlight, as temperature increases the electrons get energized and become free from nuclei, and start moving into conduction band, further as the temperature increases more electrons come into conduction; contributing to flow of current. The band gap for silicon is 1.12 eV. Band gap energy is that energy which an electron requires to free itself from the nucleus electrostatic force [34]. The measure of electron discharge depends upon the power of light occurrence on it. The silicon surface of cell is secured with a matrix that aides electrons specifically bearing to deliver electric current. These currents are further guided into a wire which is associated with battery or DC apparatus to convert DC into AC. The photovoltaic cell can be considered analogous to conventional p-n junction diode. When the surface of cell is exposed to sunlight then photons are absorbed and hole-electron pairs are formed. When these mobile charges reach vicinity of junction, the electric field will push holes to p-side and electrons to n-side as shown in Fig.2.1.The holes get accumulated on p-side and electrons on then-side on account of which voltage is generated and it can be used to deliver current to load by connecting electrical contacts on both sides of cell.

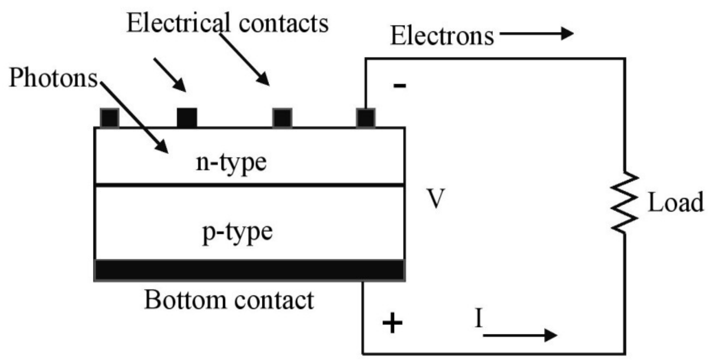


Fig. 2.1.Representation of flow of current in PV cell [34]

An equivalent model of a PV cell can be considered as a diode in parallel with current source as represented in Fig. 2.2 [35].

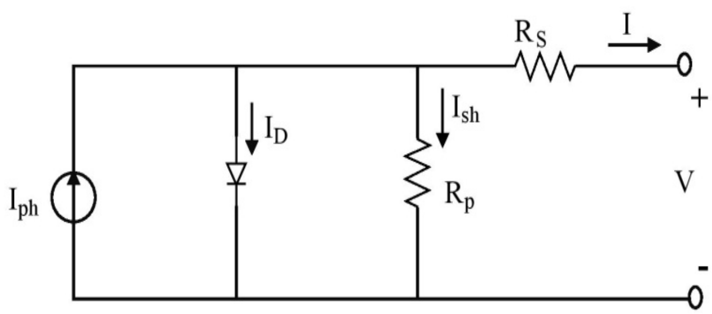


Fig. 2.2.Equivalent diagram of PV cell [35]

The equation for the model is given as:

$$I = I_{ph} - I_o \left[exp\left(\frac{V+IR_{se}}{nV_T}\right) - 1 \right] - \frac{V+IR_{se}}{R_p} \qquad (2.1)$$

where

I_{ph}: Current on account of incident light (A)

I_o: reverse saturation current of diode (A)

R_{se}: Series resistance (Ω)

R_p: shunt resistance (Ω)

n: Ideality factor of diode (usually between 1 and 2)

V_T: Thermal voltage

V: Terminal voltage

If a PV module consists of N number of cells, all of same rating then voltage of module (V_{module}) is given as: $V_{module} = N \times V_c$ where V_c is voltage of single cell.

A single PV cell produces only 0.5 V. So the cells are connected in series to increase the voltage level; this arrangement of cells connected in series is called as a cell module. A module of 36 cells can produce a voltage of 12 V. Series or parallel connection of modules is termed as array. Fig. 2.3 represents the PV cell, module and array [34]. Further, modules are connected in series to increase the voltage level and in parallel to increase current level. The series and parallel connection of modules are presented in Fig. 2.4. (a) and Fig. 2.4.(b) respectively.

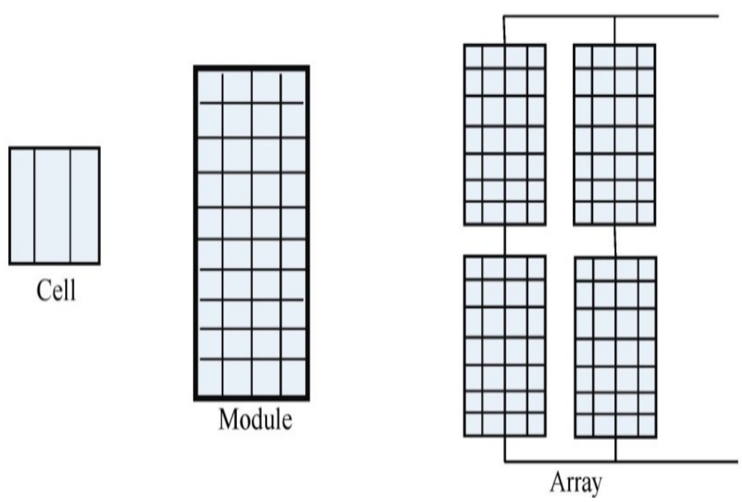
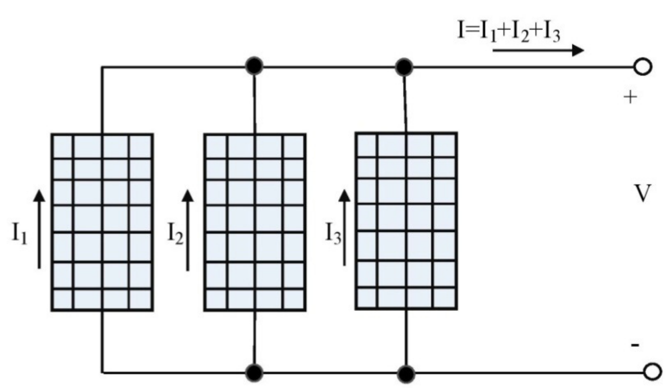
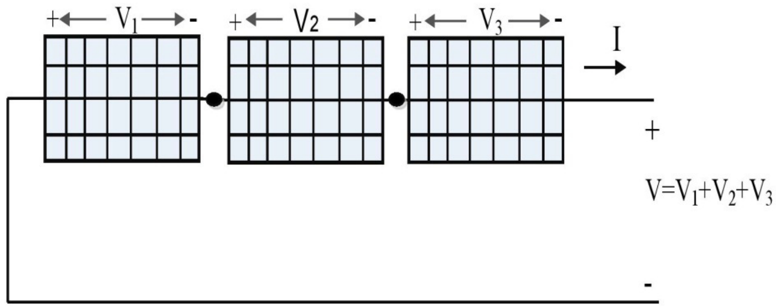


Fig.2.3: PV cell, Module, Array [34]



(a)



(b)

Fig. 2.4.Connection of modules in (a) parallel and (b) series [34]

For simulation purpose, the solar insolation (Φ) is varied using a step signal. The value of maximum current and voltage is taken as 4.35 A and 34.5 V respectively which produce a maximum power of 150.07 W.

The transfer function for PV system is given as [36].

$$G_{PV} = \frac{K_{PV}}{1+sT_{PV}} = \frac{\Delta P_{PV}}{\Delta \Phi} \quad (2.2)$$

where

ΔP_{PV}= Change in output power of PV system

$\Delta\Phi$ = Change in solar irradiation.

K_{PV} = Gain of the system

T_{PV} = Time constant

2.2 WIND GENERATOR SYSTEM

The wind generator system produces power by the virtue of blowing winds. Wind generator units convert the kinetic energy of blowing winds into electrical energy. The blowing winds rotate the blades of wind turbine; the kinetic energy of blowing wind is captured by rotor which converts the kinetic energy into rotary motion which is further used to drive the generator [37]. The block diagram of wind generator unit is represented in Fig. 2.5. The output power produced by WTG set totally depends upon velocity of wind.

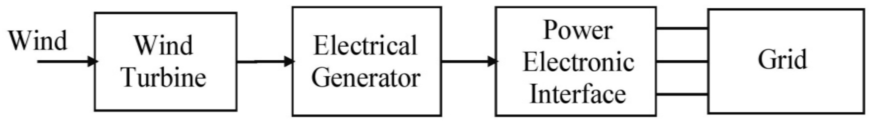


Fig. 2.5.Block diagram of wind generator system

Power contained in wind can be explained by following set of equations [38].

$$E = \frac{1}{2}mv^2 \tag{2.3}$$

$$v = \rho sV \tag{2.4}$$

where E represents the energy contained in wind, m represents air mass, ρ is density of air and is s is area swept by turbine.

So wind power is given as:

$$P = \frac{1}{2}\rho sv^3 \tag{2.5}$$

The kinetic energy of wind is converted into mechanical torque. To calculate torque of turbine mechanical power of turbine is used.

The output power of wind generator is calculated using the following equations

$$V_w{=}0.24\rho\pi R^2V^3 \tag{2.6}$$

$$0.5C_{P(\lambda,\beta)}{=}0.24 \tag{2.7}$$

In equation 2.7, C_p is the power coefficient and is used to calculate the efficiency of wind turbine system. Hereλ is tip speed ratio and β is rotor blades pitch angle.

For simulation a wind generator unit of 100 kW is considered. To study the effectiveness of proposed control scheme a variation in wind speed is considered using a unit step function. The wind turbine generato0r unit is represented in form of transfer function as [36].

$$G_{WTG} = \frac{K_{WTG}}{1+sT_{WTG}} = \frac{\Delta P_{WTG}}{\Delta P_W} \tag{2.8}$$

ΔP_{WTG} =Change in output power of wind generator system.

ΔP_W =Change in mechanical power of wind turbine.

2.3 DIESEL GENERATOR SYSTEM

Diesel engines are internal combustion engines and work in four cycles i). intake ii).compression iii).combustion iv).exhaust. Fuel consumed by engine is represented as function of mechanical power at output and speed of the diesel engine system. Usually the diesel engine model is represented using first order equation that gives relation between fuel consumption and mechanical power output. The output power of engine and generator vary with change in load requirement. A governor is used to regulate the fuel flow to engine so that output power of engine can increase or decrease depending upon load requirement [39]. There is a time delay between fuel injection and torque production which is termed as dead time. On account of presence of dead time the system becomes non linear. In order to minimize steady state error in speed a controller unit is used along with diesel engine generator set.

In order to model a diesel engine there are a certain set of equations. The actuator equation represents a relation between fuel consumption and current [40]. Where fuel flow$\emptyset(s)$ is taken as output and current $I(s)$ as input.

$$\emptyset(s) = \frac{K_1 K_2}{(1+s\tau_1)} I(s) \tag{2.9}$$

K_1 is gain of system, τ_1 is time constant and K_2 is constant for current driver.

This fuel flow is then converted into mechanical torque$T(s)$ given by equation:

$$T(s) = \emptyset(s) K_3 e^{-s\tau_2} \tag{2.10}$$

τ_2 is constant for engine torque and K_3 is constant for fuel flow.

The block diagram of diesel engine model is presented in Fig. 2.6. It represents different components of a diesel generator set. The error (change in frequency) is fed to the actuator which regulates the flow of fuel to engine in order to control the output power in response to change in frequency. Flywheel is used in conjugation with engine in order to store the surplus power and deliver it back to the system when generation is less.

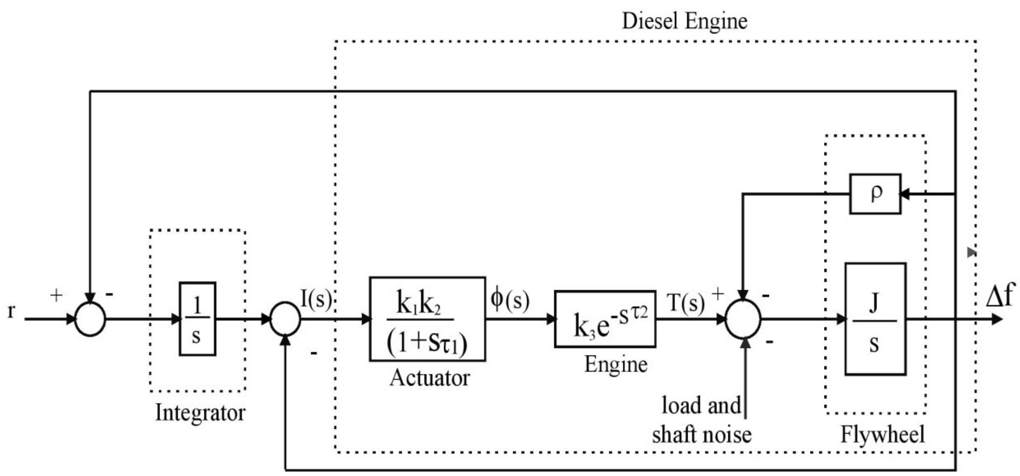


Fig. 2.6.Block diagram of diesel generator set [40]

For simulation, a diesel engine with generating capacity of 160 kW is considered. The value of R i.e. regulation constant is taken as 3. Regulation constant is provided as a feedback to governor which provides temporary droop control and prevents system instability. But for large variations, a proper control scheme is required. Since in microgrid system there is large frequency deviation so to compensate it, a fuzzy-PI based controller is used which provides information to governor for regulating the fuel flow; which in turn increases or decreases the output power depending upon the variation in frequency. Diesel generator unit is installed along with renewable sources of energy in order to ensure continuous supply of power. Since PV and wind system depend upon environmental conditions so when the conditions are not favorable the renewable units may not be able to generate required power then the diesel generator copes up with the load requirement and ensure continuous supply of power to loads.

The transfer function for DEG is presented by equation (2.11) as per [36].

$$G_{DEG} = \frac{K_{DEG}}{1+sT_{DEG}} = \frac{\Delta P_{DEG}}{\Delta f} \tag{2.11}$$

where

ΔP_{DEG} =Change in output power of DEG.

Δf = Deviation in system frequency.

2.4 STORAGE SYSTEM

With increasing trend of power generation from renewable energy resources the need of storage systems has increased in order to increase system reliability [41]. There are large numbers of storage units available. While selecting a storage system some of the main considerations are cost, size, storage capacity, efficiency, reliability and life of storage system [42]. In order to ensure a high frequency power and absorb or supply transients associated with high power a high energy density battery is required.

Since the proposed microgrid model consists of two renewable based generating units it makes system unreliable as power output of the units vary. So storage units are added to the system which stores the power when power generated by generating units is more than load demand, the storage units supply back the same power when generation is less [43]. In this work two storage units namely battery storage system and flywheel storage are considered. Both units have a generating capacity of 45 kW each. The lead-acid battery is one of the oldest and widely used battery storage systems. Its application varies from small to large systems.

Flywheel storage is also commonly used for storage system. Flywheel is a rotating system that is used to store the rotational energy. Flywheel storage units have a good efficiency (90%) and long life time. It accounts for frequency deviations and also smoothes the power delivered to grid. A flywheel energy storage system (FESS) inculcates a flywheel rotor, an inverter and an induction motor, bearings, housing. The main objective of FESS is to deliver a smooth power to grid and prevent issues like voltage and frequency deviation by storing or delivering the power. Fig. 2.7 depicts the structure and components of the flywheel system.

The energy stored by flywheel depends upon shape and material of rotor [44]. The energy stored by flywheel is given as;

$$E_k = \frac{1}{2} I \omega_2 \tag{2.12}$$

$E_k$is the kinetic energy stored, ω is the angular velocity and$I$ is moment of inertia. The rotor material decides the maximum speed at which a flywheel can operate. An electric machine is coupled with flywheel which helps in energy conversion and charging of flywheel. During the charging process the machine connected with flywheel acts as a motor and accelerates the flywheel which helps in storing the energy, by drawing electrical energy from source. During the discharging process the same machine acts as generator and extracts the stored energy by decelerating the flywheel. In wind turbine applications, generally an induction machine is used which helps to sooth the power generated by wind system.

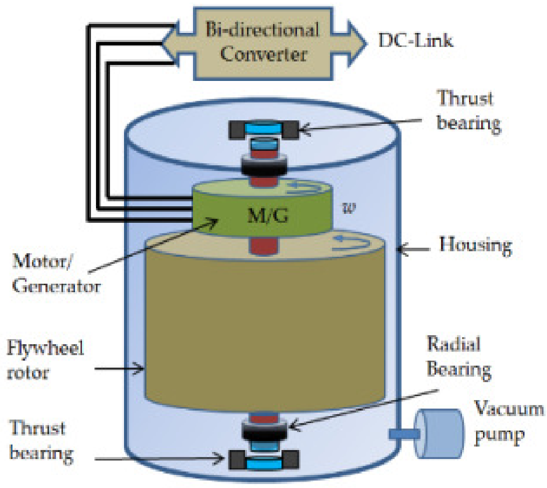


Fig. 2.7.Structure of flywheel system [44]

The flywheel systems also use power converters topologies. Some commonly used topologies are AC-AC, DC-AC, and AC-DC-AC. These topologies can also be used in combination. Depending on the application, the switching devices can be selected. Most commonly used switching devices are IGBT as they offer an advantage of handling high power and also their switching frequency is high. The most used power converter topology in FESS is AC-DC-AC or it is also called back to back configuration. In microgrids, a DC-AC converter that is an inverter is used along with FESS to provide AC power directly to the load.

Another important component of FESS is the bearings. Bearings facilitate the rotor to stay in place as there is very low friction. So bearings basically provide a support mechanism for flywheel. There are two types of bearing systems i.e. mechanical and magnetic. Since the enclosure has vacuum so gas bearings cannot be used. Nowadays, a hybrid of magnetic and mechanical bearings is used. Superconducting magnetic bearings are extensively used bearings because they offer large number of advantages like long life, no friction, compact and high speed.

Housing is used in FESS to provide two purposes first; they provide an environment where gas drag is low and in event of failure for keeping rotor under control. If flywheel is used under normal conditions the losses increase so it is mounted in a vacuum enclosure to increase safety and performance of system. The housing is made of thick steel. Since system is operated under low pressure so an effective system of cooling and vacuum pump is required. The cooling system is used to eliminate the heat generated by motor-generator set or other parts of FESS. The requirement of vacuum pump depends on the type of the rotor applied in the system like composite rotors require a low vacuum pressure as they have tip speed. A mixture of helium and air can also be used as it will serve purpose of both cooling and reduce losses.

For simulation of FESS and BESS transfer functions as given in equations (2.13) and (2.14) respectively.

The transfer function for flywheel system is [36]:

$$G_{FES} = \frac{K_{FES}}{1+sT_{FES}} = \frac{\Delta P_{FES}}{\Delta f} \tag{2.13}$$

where

ΔP_{FES} =Change in exchanged power of flywheel system.

Δf =System frequency deviation

K_{FES}= gain of system

T_{FES} = time constant of system

$$G_{BES} = \frac{K_{BES}}{1+sT_{BES}} = \frac{\Delta P_{BES}}{\Delta f} \tag{2.14}$$

ΔP_{BES}= Change in exchanged power of batter storage system.

Δf= Deviation in system frequency

2.5 MICROGRID SYSTEM

Power system shown in the microgrid model presented in Fig.2.8 represents the inertia and damping associated with the microgrid system. System inertia is one vital part of microgrid system as it is the one parameter on which synchronized operation of power system depends. Inertia is basically related with moving or rotating bodies like generators and turbines. The inertia of these bodies determines frequency response of the system [45]. On occurrence of any frequency deviation in system these synchronous machines will either absorb or inject kinetic energy from or to power system to restore frequency to its nominal value.

Although a controller is implemented for frequency control of system but there may be a situation where controller is not yet activated; in such a situation a temporary control of frequency deviation is provided by generators by absorbing or releasing kinetic energy. This is known as inertial response because frequency restored by virtue of inertia [46].

Variation in frequency following an imbalance in generation and load is given by (2.15) equation

$$P_g - P_l = \frac{d\left(0.5 J_{sys}.\omega^2\right)}{dt} \tag{2.15}$$

Here $P_g$is power generated,$P_l$is load demand power, J_{sys} is inertia of system and ω is the electrical angular frequency. The derivative term depicts the steady state of change of stored kinetic energy in the generators.

The inertia constant for a system is depicted in seconds. For a large power system it takes a value of 2-9 sec; for any given system the inertia depends on two factors first, the number of generators present in the system and second on inertia of individual generator unit. The photovoltaic and wind generator systems which use converter units, have the generator units electrically decoupled so they offer no inertia response. So low inertia is one problem associated with renewable based generations.

Damping in system can occur on account of any fault condition in the system.

Equation 2.16 represents transfer function for power system [36].

$$\Delta f = \frac{1}{D+2Hs} \tag{2.16}$$

D = Load damping constant

$2H$= inertia constant

2.6 MICROGRID ARCHITECTURE

Two configurations of microgrid system are considered. First a single area microgrid consisting of PV, wind, diesel generator set along with storage units is discussed and in the next section (2.6.2) two-area MG system configuration is presented, consisting of PV, diesel generator set and battery in area-1. Area-2 consists of wind, diesel engine and flywheel storage system. Fuzzy-PI and autotuned-PI controller are used for both the microgrid configurations.

2.6.1 SINGLE AREA HYBRID MICROGRID SYSTEM

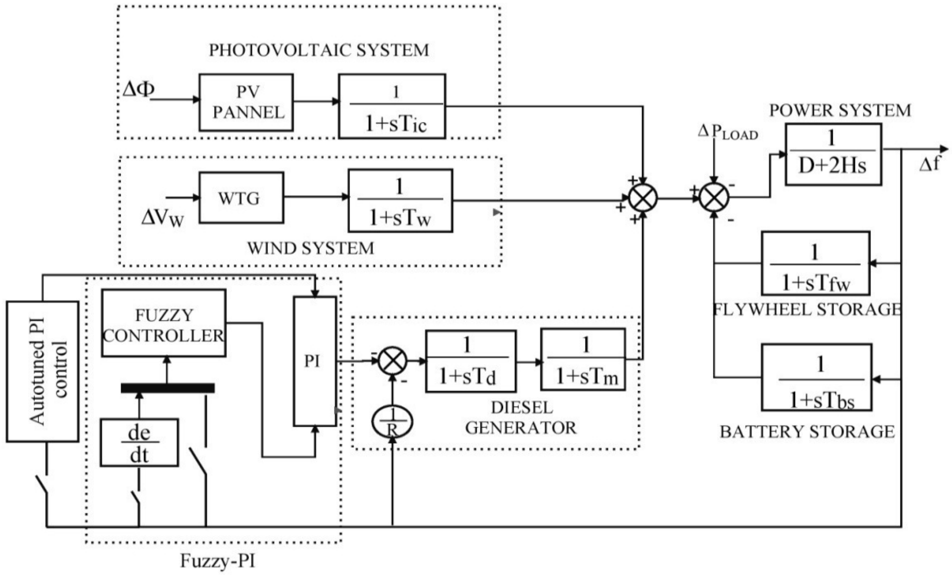


Fig. 2.8.A proposed single area hybrid microgrid model

An AC microgrid as shown in Fig. 2.8 is considered. MG is feeding a load with peak demand of 350 kW. Photovoltaic based generation system has a solar panel of 30 kW power rating. Wind generator of 100 kW capacities is used. The photovoltaic and wind generator systems are primary sources of power generation. A diesel generator system of 160 kW rating is added in the system for backup purpose. Along with diesel generator set two storage units namely flywheel and battery storage system are also considered. The power rating for both these units is 45 kW each. The microgrid also accounts for the damping and inertia of system which is represented by power system block in Fig. 2.8. The mathematical model of system is considered and the entire system is depicted in form of transfer function. All the values used are in per unit. The controller unit is connected with diesel generator set.

2.6.2 TWO AREA HYBRID MICROGRID SYSTEM

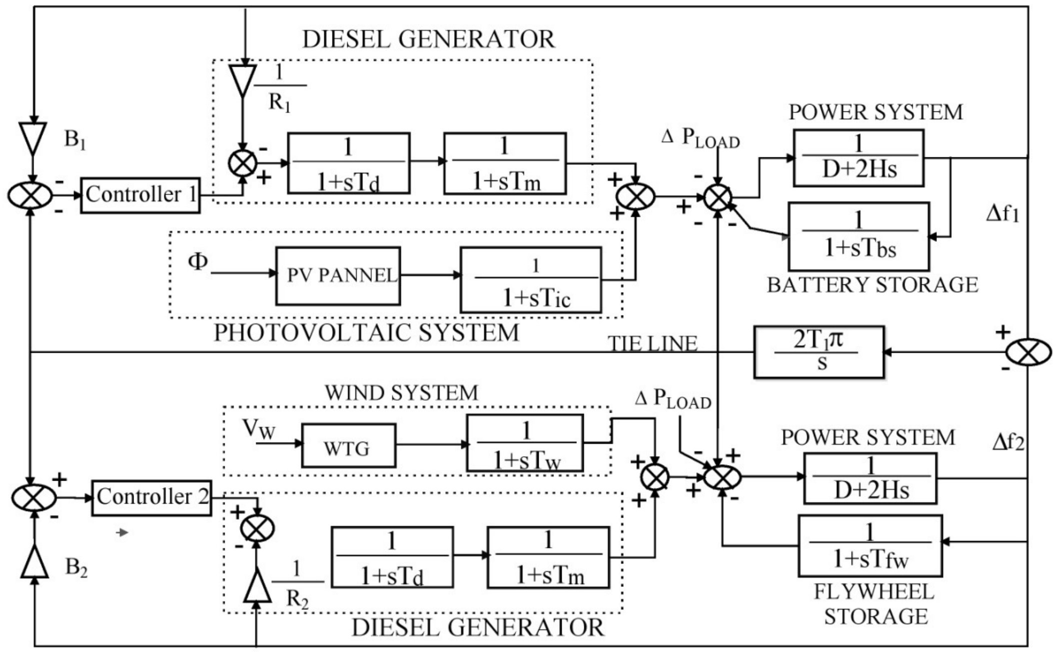


Fig. 2.9.A proposed two area hybrid microgrid model

In two area system, two combinations of DERs are connected through tie-line as shown in Fig.2.9. Tie line is a transmission line that connects both the areas. The two MGs are interconnected to increase reliability of the system. The tie line is represented using a transfer function, known as synchronizing transfer function. It helps the exchange of power between two interconnected units. The tie line used is DC, so the power output form one substation is converted from AC to DC and then back to AC. The area-1 consists of a PV unit, a diesel generator set and a battery storage system. Wind generator set, diesel generator unit and flywheel storage system is employed in area-2. The system employs the use of two controllers one for each area. The controllers are connected with diesel engine in each area. Two different control schemes are used for frequency control of the system. The main objective of LFC in two area microgrid system is to maintain frequency change in both areas to zero on occurrence of any change in load and variation in DERs. Each area must be capable of absorbing the change in system load so that frequency does not deviate from its nominal value. Also the tie line power should be maintained at its constant value. The parameters used for both the microgrid systems are presented in Table 1.

TABLE 1 PARAMETERS OF PROPOSED MICROGRID SYSTEM

PARAMETER	VALUE (p.u.)
T_m	0.42
T_d	0.081
T_{ic}(s)	0.004
T_{fw}(s)	0.1
T_{bs}(s)	0.12
R(Hz/pu)	3
D(pu/Hz)	0.0156
T_i(s)	0.041
2H(pu/s)	0.166
B_1	0.4249
B_2	0.4249
R_1	3
R_2	3
T_{12}	0.087

Table 1 presents the parameters used for both single area and two-area microgrid system. The values for time constants of all the transfer functions used are listed in the table. For single area system the regulation R is used. There are two regulation constants R_1 and R_2 for both area-1 and area-2 in two area microgrid. Similarly, there are two frequency bias constants B_1 and B2. These constants regulate the power flow between the two interconnected areas. Generally, the value of bias and regulation for both the areas is same.

CHAPTER 3- METHODOLGY ADOPTED

A lot of frequency control techniques are available. Earlier techniques, like frequency droop control and tie-line frequency control were used. These systems were slow, complex and not very efficient. With advancements in power system the need for intelligent controllers has emerged. In this work fuzzy-PI controller is proposed. The proposed controller is validated using autotuned-PI controller in MATLAB-simulink environment. The detailed discussion about both the control scheme is presented in sections 3.1 and 3.2.

3.1 FUZZY-PI BASED CONTROLLER

For a PI controller, the values of P and I are generally pre-assigned. If any fluctuation occurs in the system, the PI controller is not able to take account of them and hence the performance of controller degrades [48]. Therefore, we use fuzzy based PI controller which provides an intelligent control by updating the PI controller parameters if there is any variation in system operation condition. As represented in Fig. 3.1, fuzzy system output is provided as an input to PI controller which further controls the plant with updated values of P and I.

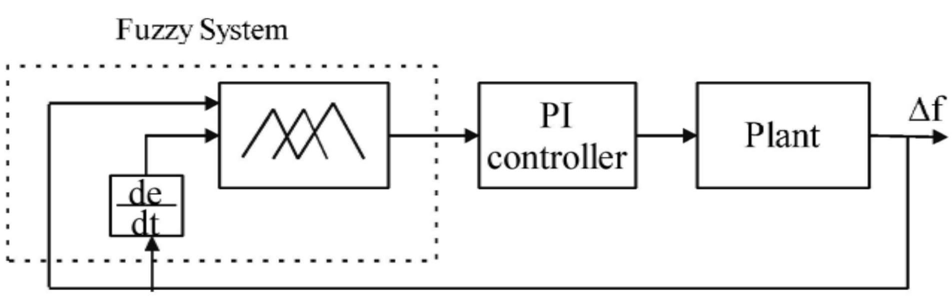


Fig. 3.1.Block diagram for Fuzzy-PI control scheme [48]

A fuzzy controller consists of four main elements which are discussed below [49].

3.1.1 FUZZIFICATION

It is the process of converting the user inputs provided to the controller; into a form that inference system can understand and implement the rules provided.

3.1.2 RULE BASE

It is a set of 'if' and 'then' rules, which consists the fuzzy logic representation of users description on attaining the best possible control. The performance of controller depends on how well the rules are defined. The rules may be prepared by first observing the system behavior under normal conditions without implementation of controller. Rule base for proposed control scheme is represented in Table 2. There are total 98 rules; for which 49 rules are set for K_p and remaining 49 rules are framed for K_i.

3.1.3 INFERENCE MECHANISM

It imitates the user's idea of attaining a best possible control, in order to understand and apply the rules for achieving a good control.

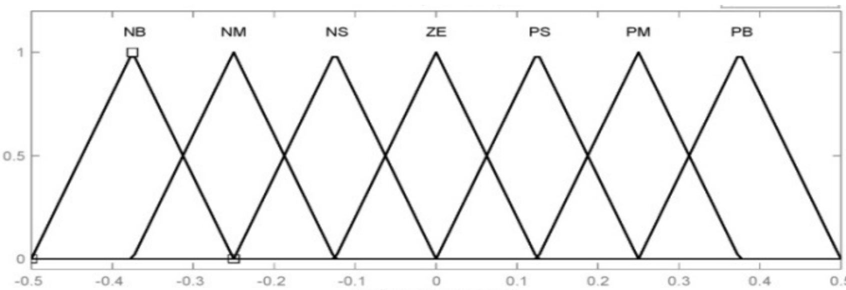
3.1.4 DEFUZZIFIZCTION

It is the process which finally provides the input to the system, by converting the decision of inference system. For the proposed control scheme the set of inputs considered are error (change in frequency) and rate of change of error. These inputs are provided to fuzzy logic controller. The inputs are fuzzified using seven membership functions. Membership function is basically a curve that depicts how each point of input is mapped into a membership value between 0 and 1.

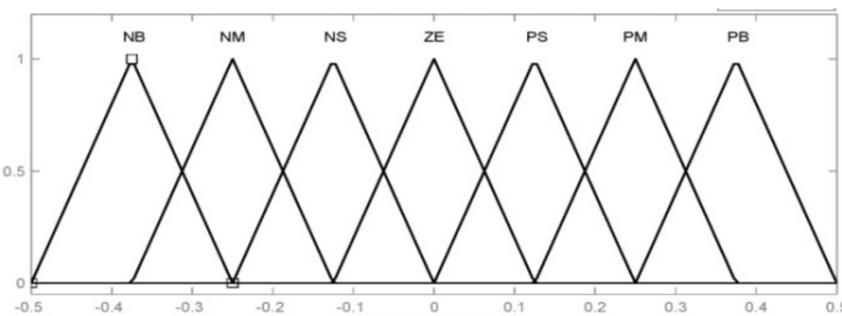
For the proposed control scheme a set of seven membership functions is considered for input signals, namely Positive big (PB), Positive medium (PM), Positive small (PS), Zero (ZE), Negative big (NB), Negative medium (NM), Negative small (NS). All the membership functions used are triangular.

The output is fuzzified using three membership functions negative (N), zero (Z) and positive (P). The membership functions used are both triangular and trapezoidal. The fuzzy inference system used is mamdani. The membership functions for input and output are depicted in Fig. 3.2.

For example, in rule one, 'if' the error and change in error are both negative big (NB), then K_P is negative and K_i is positive. Which means that if value of error and change in error lies between -0.5 and -0.5, then the value of K_p shall lie between 0 and 1, the value of K_i should fall in range of 2-8. The range for K_p and K_i is decided based on the response of system under different values of K_p and K_i. Depending on different disturbances in the system the value of error and change in error vary, based on which different rules are updated and the values of control parameters i.e. K_P and k_i are computed.



(a)



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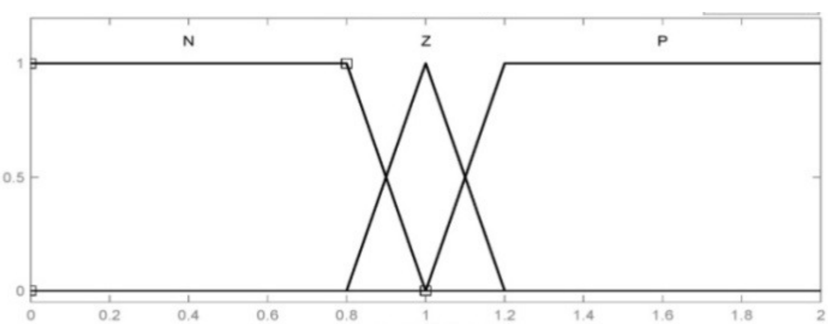

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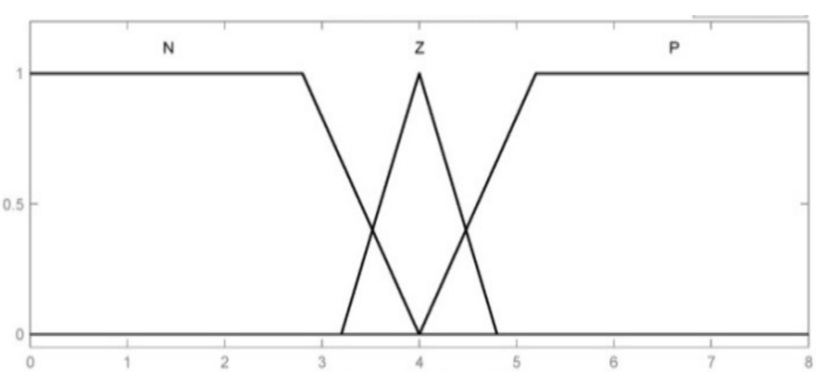


(d)

Fig. 3.2.Membership function for (a) error, (b) change in error, (c) Kp, (d) K_i

TABLE 2 RULE BASE FOR PROPOSED CONTROL SCHEME

K_p / K_i	e / ce	NB	NM	NS	ZE	PS	PM	PB
NB		N	Z	N	N	N	Z	P
		P	Z	N	N	N	Z	P
NM		P	P	Z	N	Z	P	P
		P	Z	Z	N	Z	Z	P
NS		P	P	Z	N	Z	P	P
		P	P	Z	N	Z	P	P
ZE		P	P	P	Z	P	P	P
		P	P	P	Z	P	P	P
PS		P	P	Z	N	Z	P	P
		P	P	Z	N	Z	P	P
PM		P	P	Z	N	Z	P	P
		P	Z	Z	N	Z	Z	P
PB		P	Z	N	N	P	Z	P
		P	Z	N	N	P	Z	P

3.2 AUTOTUNED PI

Autotuning is a process that automatically computes the value of control parameters for any given system, to bring out the best possible control, without user interaction. User interaction may only be required to initiate the process. It is much more efficient and reliable as compared to manual computation of parameters [50].

Autotuning process basically includes three main steps:

1. Choosing the model to be processed

2. Collecting the data associated with the process and fitting it into the model.

3. Computing the control parameters.

The process identification is done basically by two methods; such as step response method and relay feedback method.

The data about the process can be provided either by triggering the process intentionally or by observing the process behavior under normal conditions. After the attainment of data, it is converted into process description.

The tuning rules can be formulated in three ways:

1. Tuning the parameters in such a way that our process output matches with the reference model used.

2. Computing parameters based on some closed loop system description.

3. Tuning based on human description.

All these methods are based on solving a certain set of equations.

The system under consideration is tuned for all the three cases considered and a set of P and I parameters is attained for all the three cases.

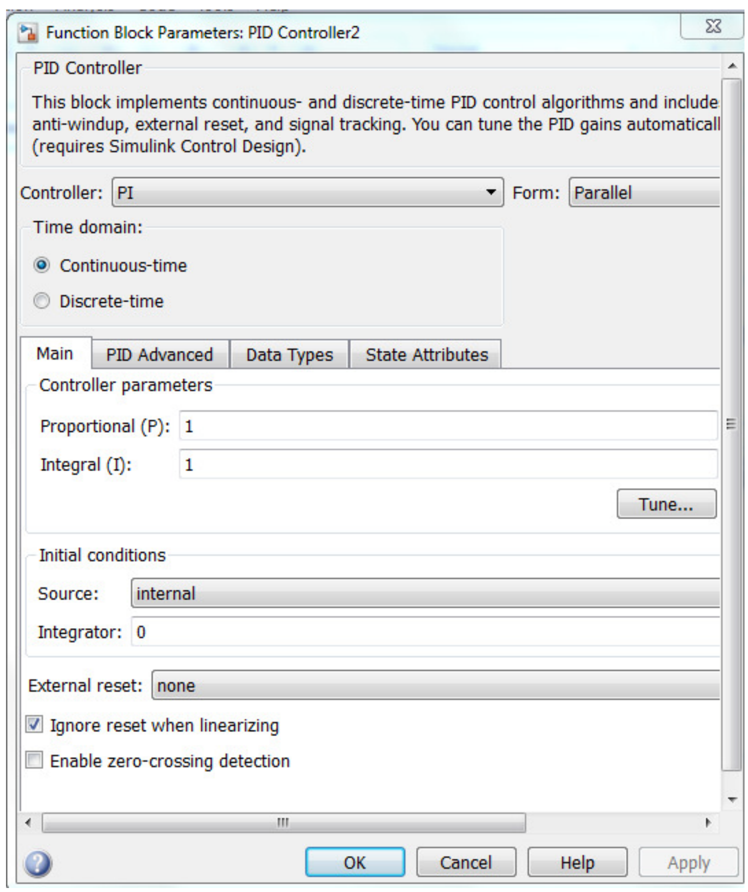


Fig. 3.3.PI controller block readily available in MATLAB/ simulink library

The tuning of PI controller is done automatically using the PI controller block readily available in MATLAB/simulink library as presented in Fig.3.3. The controller block presents facilities for tuning of parameters based on internal or external commands. The parameters are updated automatically when tuning is done internally. User needs to specify the mode as 'internal' and press on the 'tune' option available. In case the parameters are to be attained based on external commands then the mode is selected as external and certain commands should be available based on which parameters can be updated. As discussed in section 3.1, values of P and I are updated based on rule base defined. The tuned values of P and I attained vary for single area and two area system are tabulated and are presented in result and discussion section.

3.2.1 CONTROLLER MODES

PI controller uses proportional (P) mode and integral mode (I) for computing a control signal. The PI control signal is computed as presented in equation (2.17)

$$u(t) = K_P e(t) + K_i \int e(t)dt \qquad (2.17)$$

The above equation can be written in equivalent form as presented in equation in (2.18)

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int e(t)dt\right) \qquad (2.18)$$

3.2.1.1 PROPORTIONAL MODE

The control law for proportional mode is given by equation (2.19)

$$u_p(t) = Ke(t) + U_b \qquad (2.19)$$

where

$u_p(t)$ is the output of proportional controller.

K represents the gain of the system and

$U_b$is the bias or reset value.

The P makes the action of controller proportional to the error. The P action depends on instantaneous values of error. Only for non zero values of error the output value of controller will be non zero. This means that the value of P at steady state will be zero but this is not feasible. So in order to maintain value of P controller at a constant level a bias is added to the system. Which means that even if value of error is zero the value of controller output will be some constant and hence maintain the controller action. But if an integral controller is also used in conjugation with P controller then there is no need to add an external bias the reset is attained by action of I controller. Some characteristics of P control are:

1. Increasing the value of P control will reduce the steady state error.
2. Increasing the value of P beyond certain point will only result in increased overshoot.
3. It helps in reducing the rise time.

3.2.1.2 INTEGRAL MODE

The output generated by integral action is proportional to accumulated error as presented in equation (2.20). The I-control signal is given as:

$$u_1(t) = \frac{K}{T_i} \int e(t) + u(0) \tag{2.20}$$

The integral controller takes into account the sum of all the errors. When input of integrator is e, steady state cannot be achieved unless e is non-zero. So it ensures a zero error at steady state. The I-control not only considers the present value of error but also accounts for the previous value of error. The action of I controller is slow and it does not respond to sudden changes quickly.

Some key features of the I-controller are:

1. It helps in eliminating the steady state error.
2. Increasing the value of I beyond certain limit leads to increase in overshoot.
3. It reduces the rise time.

3.3 INTEGRAL OF TIME WEIGHTED ABSOLUTE ERROR (ITAE)

The ITAE can be presented in equation (2.21)

$$ITAE = \int_0^\infty t|e(t)dt| \tag{2.21}$$

where t represents time and $e$is the error which is generated on account of difference between reference and output attained.

ITAE is used to reduce the error associated with the system, by calculating the best possible values for P and I in order to achieve best possible control. The ITAE values for different cases considered in system are calculated to carry out comparative analysis between the proposed control scheme and autotuned-PI scheme.

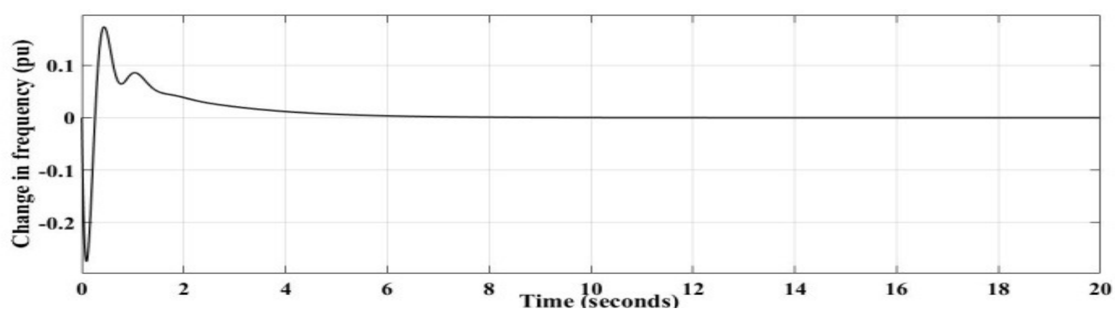
CHAPTER 4- RESULTS AND DISCUSSIONS

For performing simulations of single area system, three different cases have been considered by varying input signals of PV, wind and change in load. For two area microgrid four different cases are studied based on variation in input signals of area 1 and area 2. To carry out comparative analysis for Fuzzy PI and autotuned PI controller the results of both the schemes have been explained. The effectiveness of proposed control scheme is illustrated by simulating the model in MATLAB/simulink environment using Sim-Power blocks.

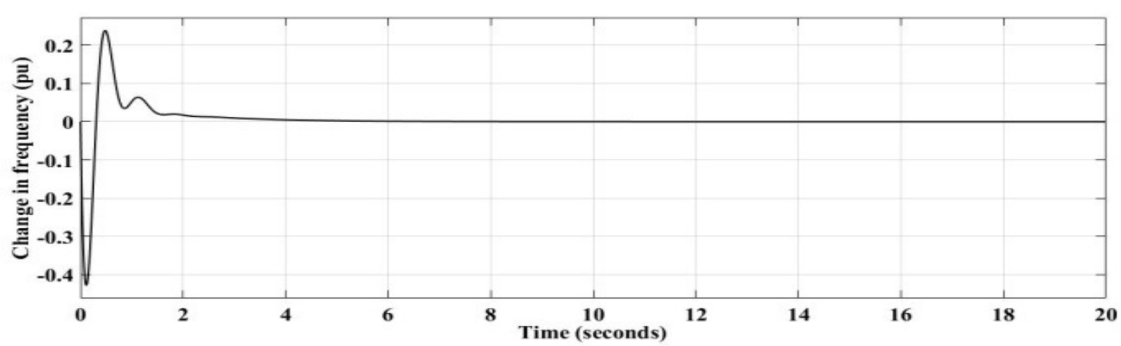
4.1 SINGLE AREA HYBRID MICROGRID SYSTEM

CASE I

As presented in Fig. 2.8, the model is simulated by considering a disturbance of 0.2p.u. in load and keeping other two signals i.e. solar insolation and wind speed constant to value of 1000W/m^2 and 10m/s respectively.



(a)



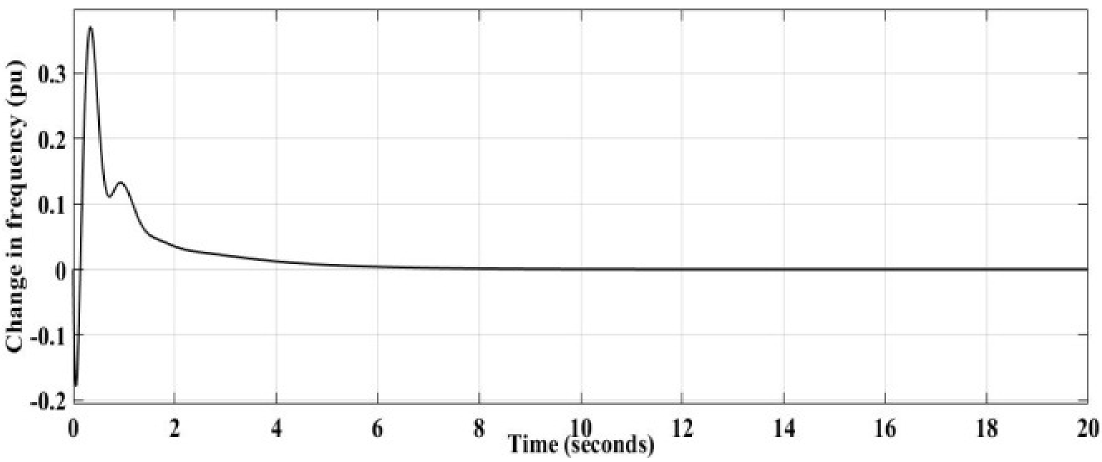
(b)

Fig. 4.1.Change in frequency vs. time graph for (a) Fuzzy-PI controller (b)autotuned-PI controller

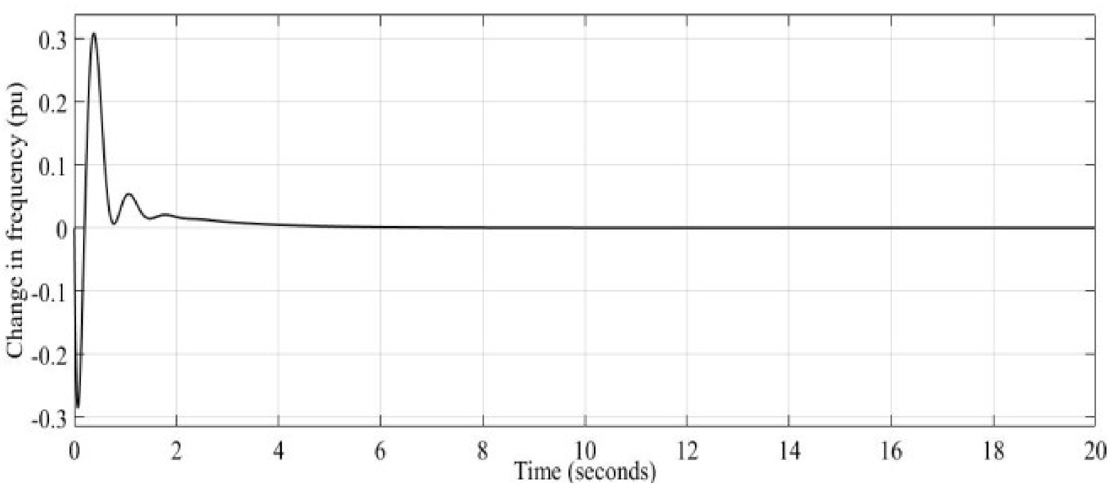
Both the systems are studied and the values of ITAE are observed. The outputs for both the schemes are presented in Fig.4.1 (a) and (b). It is noted that the values of ITAE in both cases is relatively same. The autotuned scheme has better results as compared to fuzzy-PI as it provides a better steady state response.

CASE II

Under second case, the wind speed is assumed to be constant 10m/s and a change of 0.2 p.u. in both load and PV system is considered i.e. the solar irradiation is changed from a constant value of 1000W/m^2. The response for autotuned and Fuzzy-PI scheme is presented in Fig. 4.2 (a) and (b) respectively.



(a)



(b)

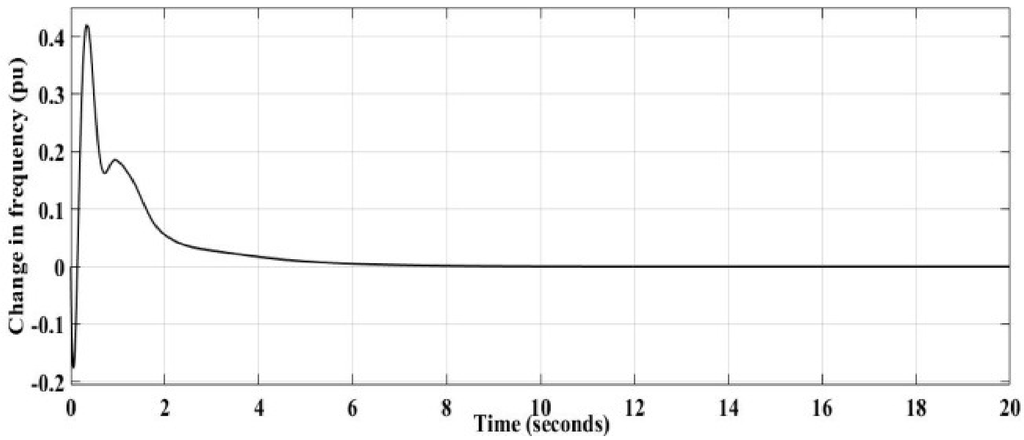
Fig. 4.2.Change in frequency vs. time graph for (b) Fuzzy-PI control scheme (b) autotuned PI

The value of PI control parameters attained and ITAE are presented in Table 3. It can be inferred from the values of ITAE that error in case of autotuned PI is less than that in fuzzy-

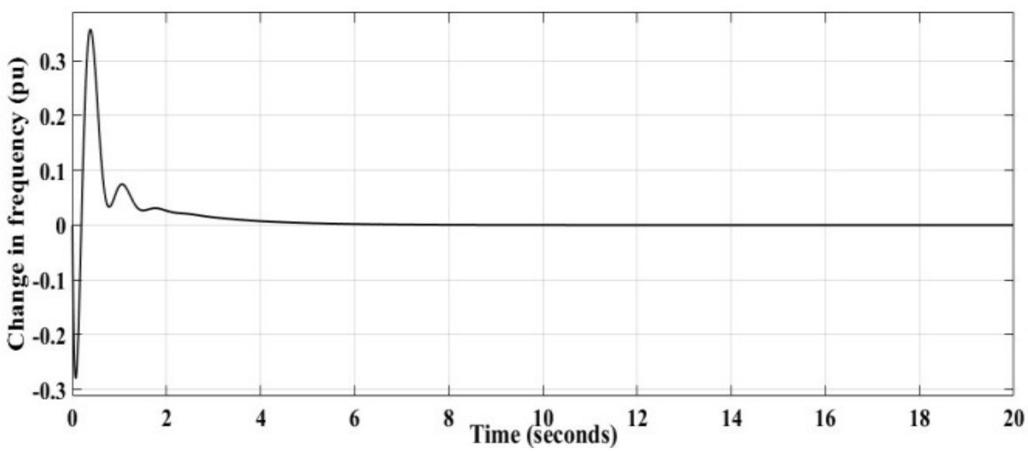
PI control scheme. But the fuzzy-PI scheme also generates a good response based on the referred system problem.

CASE III

For simulations in this case the values of solar irradiation and wind speed are varied along with variation in load. A disturbance of 0.2 pu in each signal is considered.



(a)



(b)

Fig. 4.3.Change in frequency vs. time graph for (a) Fuzzy-PI controller (b) autotuned PI

Based on the simulation results presented in Fig.4.3 (a) and (b), it can be inferred that the peak values in both the cases are almost same. Referring to values of ITAE presented in table 4 it is noted that the autotuned controller improves the performance of system by reducing the value of ITAE. The steady state response generated by autotuning of PI controller parameters is improved. But the value of ITAE for Fuzzy-PI is also close to that obtained from autotuned controller.

TABLE 3 PI CONTROLLER PARAMETERS

Case	Fuzzy- PI			AutotunedPI		
	P	I	ITAE	P	I	ITAE
I	1.000011	7.000045	0.1944	1.4999	8.7186	0.1808
II	1.000048	7.000192	0.1886	1.4999	8.7186	0.176
III	1.000028	7.000810	0.2137	1.4999	8.7186	0.2045

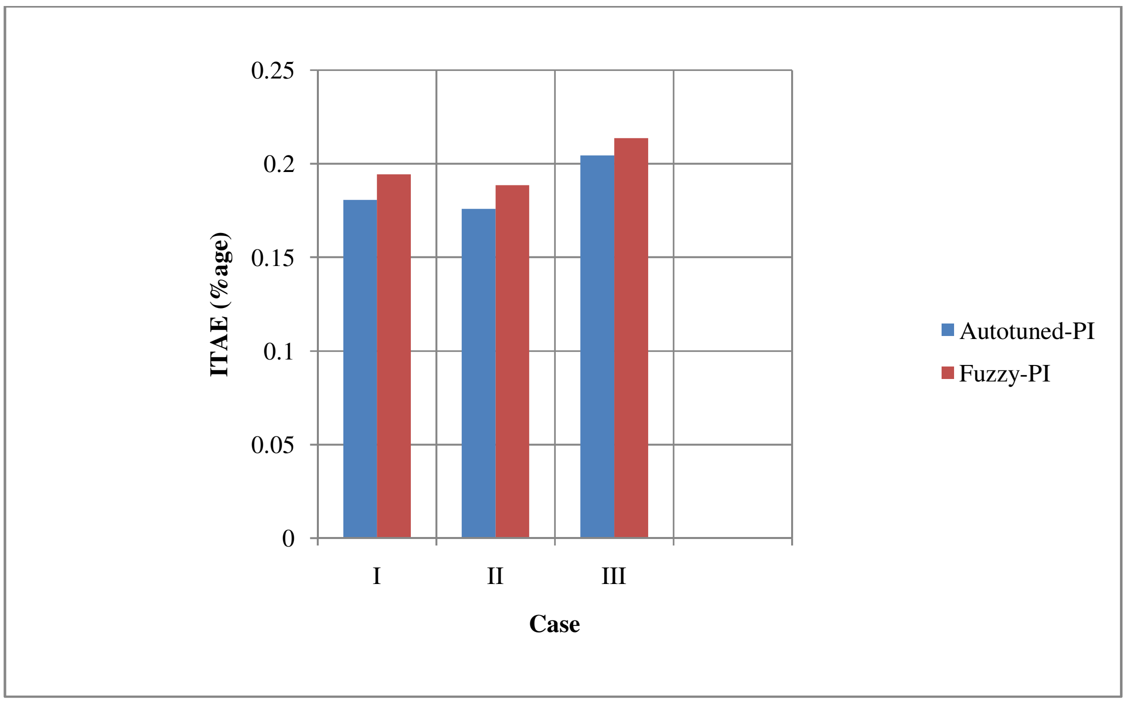


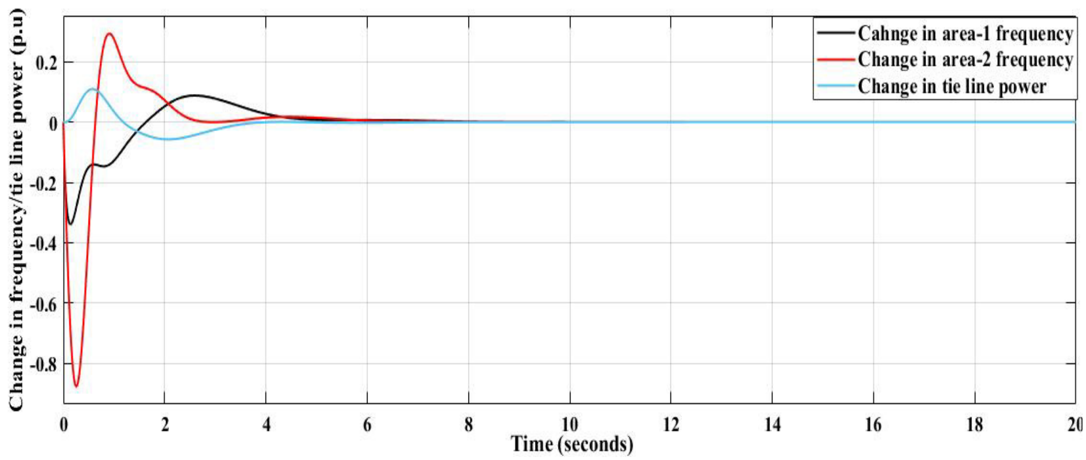
Fig. 4.4.Mapping of autotuned and fuzzy-PI based on ITAE.

It can be noted from the results presented in Fig.4.4 that the value of ITAE attained from autotuned PI is less than that of fuzzy-PI scheme. In case 3 when all the signals are disturbed, the value of ITAE is 0.2045 for autotuned-PI and 0.2137 for fuzzy-PI controller; and the percentage difference being 4%.

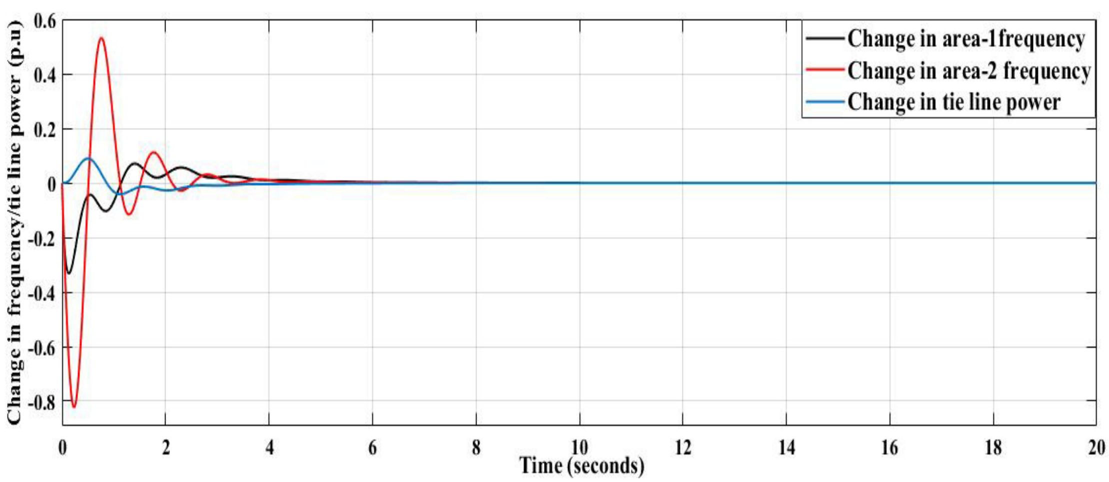
4.2 TWO AREA HYBRID MICROGRID SYSTEM

CASE I

In the first case a load variation of 0.2p.u. in area-1 is considered keeping the PV input to a constant value of 1000W/m^2. Both the signals of area-2 i.e. wind speed and loads are kept constant. The simulation results for autotuned-PI and fuzzy-PI are depicted in Fig. 4.5 (a) and (b) respectively. Considering BES (fully charged), diesel generator, PV fixed.



(a)



(b)

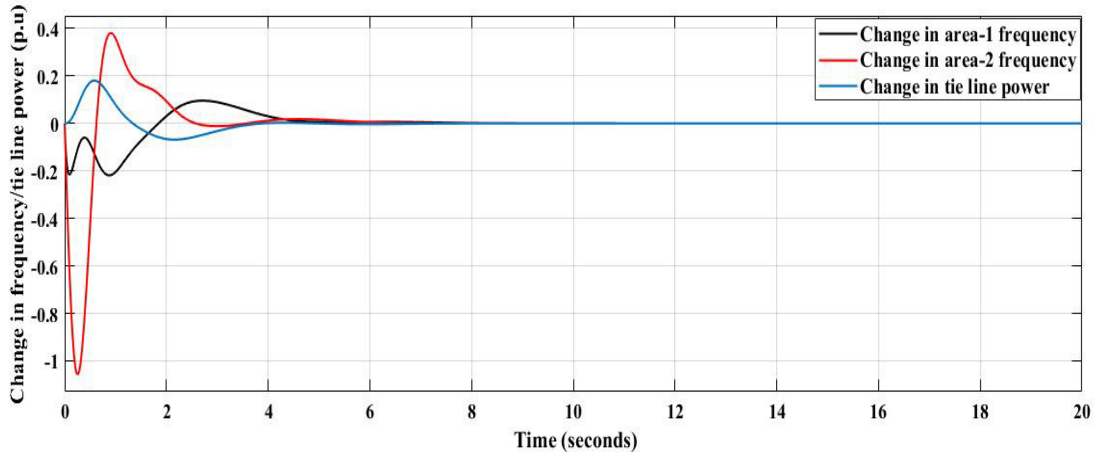
Fig. 4.5.Change in tie line power and frequency wrt time for (a) fuzzy-PI (b) autotuned-PI

It is observed from the results that peak value in case of fuzzy-PI control scheme is less as compared to autotuned-PI control scheme. Also the oscillations in case of fuzzy-PI scheme are less. The value of ITAE in case of autotuned-PI is less as compared to fuzzy-PI controller.

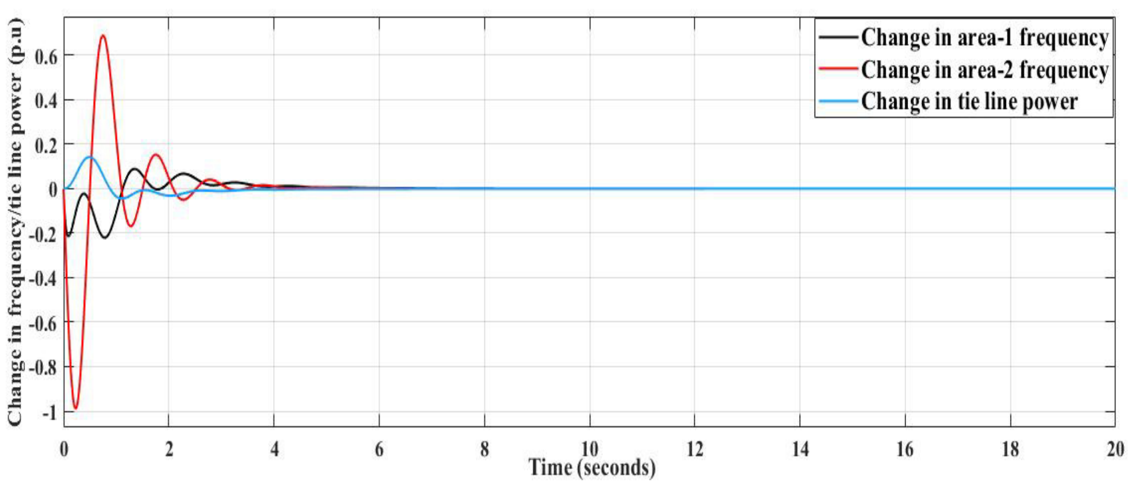
The control parameters attained for both the controllers of area-1 and area-2 for autotuned-PI are presented in Table4and for fuzzy-PI controller in presented in Table 5.

CASE II

In this case a load change is considered only in area-2. The value of wind speed is considered to be constant 10m/s. Both the signals of area 1are also considered to be constant with the value of solar irradiation 1000W/m^2. Here only area-2 is disturbed and the area-1 is undisturbed.



(a)



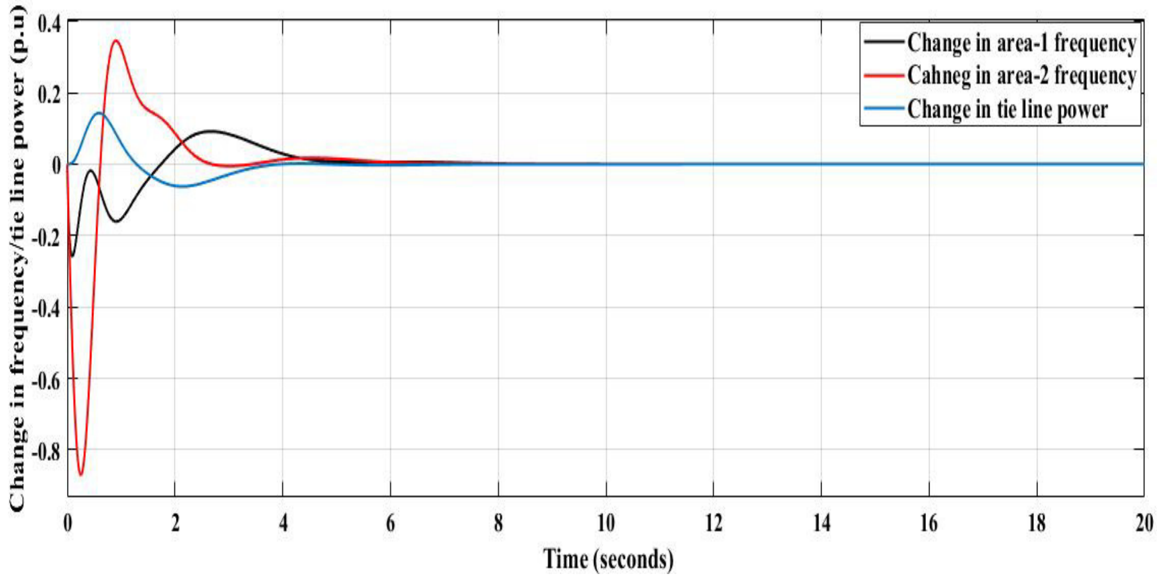
(b)

Fig. 4.6.Change in tie line power and frequency wrt time for (a) fuzzy-PI (b) autotuned-PI

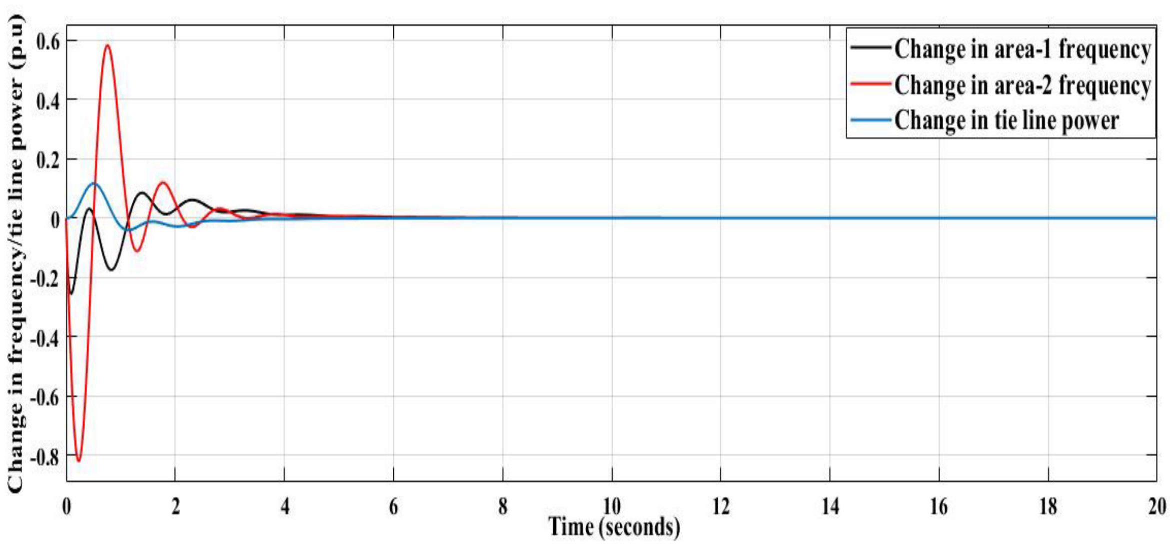
Fig. 4.6 (a) and (b) represent the results attained from both the control schemes. In this case the peak values for both control schemes area relatively same. But the value of ITAE is less for autotuned-PI scheme. Again oscillations in case of fuzzy-PI scheme are reduced. The settling time is almost same in both the cases. The values of P and I for both the controllers for each scheme are presented in Table 4 and 5.

CASE III

In this case, disturbance is considered in area-1. Both the signals of area-1 i.e. solar irradiation and load are disturbed with disturbance of 0.2p.u. the value of solar irradiation is increased from 1000W/m^2 by 20%. The input to generating unit of area-2 is kept constant to value of 10m/s, with no load disturbance in area-2.



(a)



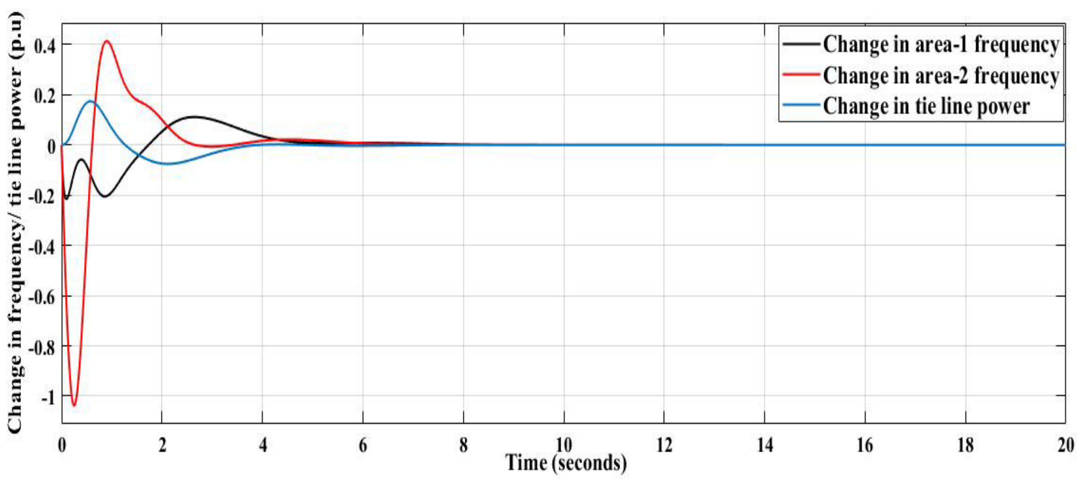
(b)

Fig. 4.7.Change in tie line power and frequency wrt time for (a) fuzzy-PI (b) autotuned-PI

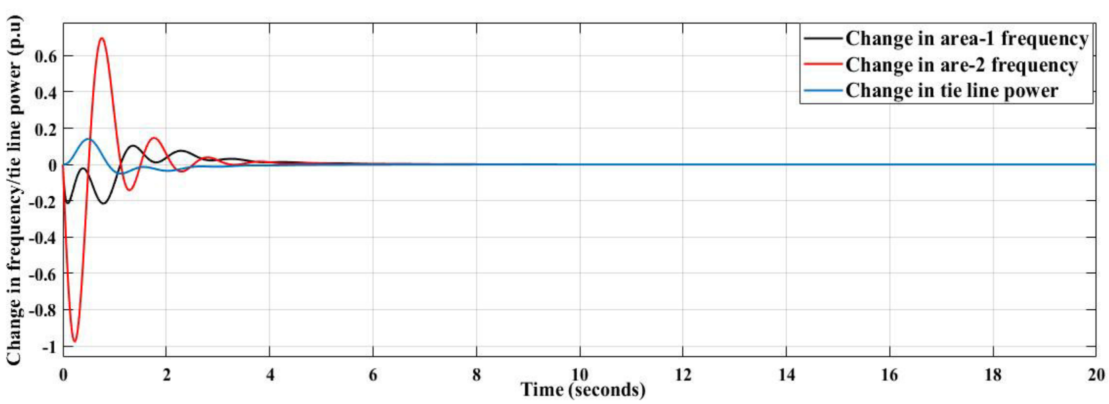
The overshoot of system decreases when fuzzy-PI controller is used. Also the oscillations in case of fuzzy-PI scheme are less as compared to autotuned-PI scheme. The results for both the schemes are presented in Fig.4.7 (a) and (b). The values of control parameters for both the schemes are presented in Table 4 and 5. Also, it can be inferred from ITAE values as presented in Table 4 and 5 that the autotuned-PI performs better and faster than fuzzy-PI controller.

CASE IV

The disturbances are considered in the input signals of only area-2. The wind speed is changed from 10m/s to 12m/s by considering a 20% increase in wind speed along with disturbance in load of 0.2p.u. in area-2. The input signals of area-1 are kept constant; where solar irradiation is 1000 W/m^2 with no change in load condition.



(a)



(b)

Fig. 4.8.Change in tie line power and frequency wrt time for (a) fuzzy-PI (b) autotuned-PI

It can be inferred from the simulation results that the overshoot in both the cases is same. The value of ITAE for autotuned-PI control scheme is less in case of both the controllers and the oscillation being relatively same. The results for both the schemes are presented in Fig.4.8 (a) and (b). The values of control parameters for both the schemes are presented in Table 4 and 5. Also it can be observed from values of ITAE that the autotunned-PI controller generates a better response. The values of P and I for both the controllers are listed in the Table 4 and 5.

TABLE 4 PI CONTROL PARAMETERS FOR FUZZY-PI CONTROL SCHEME

CASE	CONTROLLER 1			CONTROLLER 2		
	P	I	ITAE	P	I	ITAE
I	1.00023	4.00093	0.1975	1.0005	4.00020	0.376
II	1.00016	4.0005	0.1411	1.0002	4.00013	0.4204
III	1.00019	4.0008	0.1292	1.00016	4.0009	0.338
IV	1.00222	4.00088	0.124	1.0004	4.00019	0.382

TABLE 5 PI CONTROL PARAMETERS FOR AUTOTUNED-PI CONTROL SCHEME

CASE	CONTROLLER 1			CONTROLLER 2		
	P	I	ITAE	P	I	ITAE
I	2.9558	7.1682	0.07737	2.71044	7.2455	0.2859
II	2.9559	7.1682	0.1037	2.8394	7.4125	0.3201
III	2.8630	7.0239	0.09322	2.6843	7.2219	0.2936
IV	2.9558	7.1688	0.1052	2.71044	7.2455	0.3535

Table 4 and Table 5 present the values of P and I attained for both the controllers employed in area-1 and area-2 along with values of ITAE attained for both the control schemes under different cases.

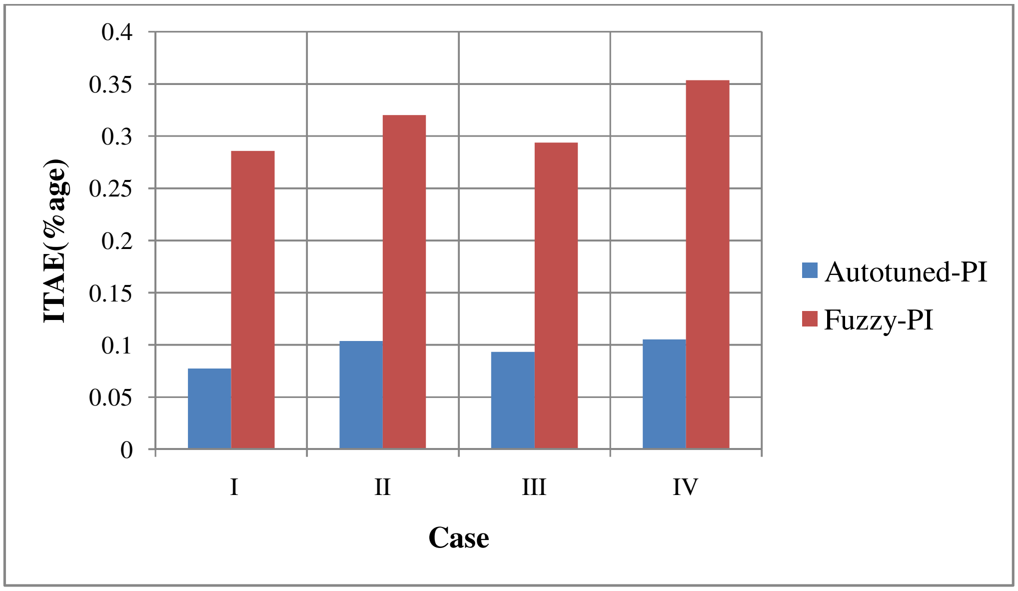


Fig. 4.9.Mapping of autotuned and fuzzy-PI based on ITAE for Area-1

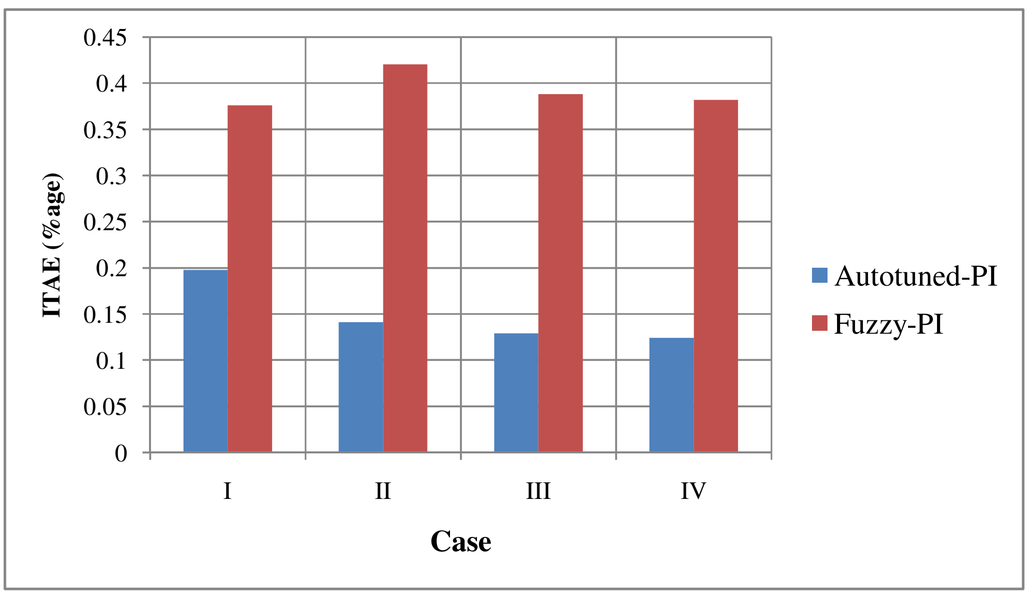


Fig. 4.10 Mapping of autotuned and fuzzy-PI based on ITAE for Area-2

It can be noted from the results presented in Fig. 4.9 that the value of ITAE in case of autotuned PI is less than that of fuzzy-PI based controller. In case 4 when all the signals of area-2 are disturbed the value of ITAE for controller 1 is 0.1052 for autotuned-PI and 0.124

for fuzzy-PI controller. Similarly, the values of ITAE for controller 2 as presented in Fig. 4.10, for autotuned-PI and fuzzy-PI are 0.3535 and 0.382 respectively.

CHAPTER 5- CONCLUSION

The integration of DER's into a microgrid system consisting of varying load can cause a frequency fluctuation issue. So a frequency controller is needed to solve this problem meeting generation and demand of an islanded microgrid system considering the fuzziness in frequency fluctuation. A hybrid microgrid system consisting of PV system, wind turbine generator set, diesel generator set along with storage facility and equipped with a proposed fuzzy-PI controller for frequency control under islanded condition is considered. The performance of fuzzy-PI controller is evaluated for both single area and two area microgrid system. Different cases for evaluating the performance of control scheme are considered based on disturbances in input signals to PV panel, wind speed and change in load. Further, the proposed scheme is compared with autotuned-PI control scheme. The change in frequency is found minimum in case of autotuned PI controller as compared to fuzzy-PI controller. The proposed fuzzy-PI controller is validated based on ITAE (4-7%) which is higher than that attained form autotuned-PI controller. It is evident from the results that both the schemes show satisfactory performance while the overshoot is found relatively same in both the cases. In future work the frequency restoration through storage system will be studied considering the effect of charging and discharging of battery storage system. The performance of proposed controller considering the effect of voltage control on the basis of reactive power will also be explored.

CHAPTER 6- LIST OF PUBLICATIONS

Scopus Indexed Journal:

1. Jashandeep Kaur, Jitender Kaushal, Prasenjit Basak, "Frequency Control of Microgrid under Islanded Condition using Fuzzy-PI and Autotuned Controllers", The ECTI Transactions on Electrical Engineering, Electronics & Communications, ***(Communicated on 13th June, 2017).***

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M.E.dissertation

ORIGINALITY REPORT

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