DESIGN OF CONTROL STRATEGIES FOR FREQUENCY STABILITY OF PV-THERMAL INTERCONNECTED POWER SYSTEM

By

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A dissertation Submitted in the fulfilment of the requirements for the degree of Master of Engineering in Electrical Power Engineering

In the Department of Electrical Power Engineering

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February 2021

DECLARATION

I would like to declare that this thesis is my work and has never been published before. Moreover, this work is referenced. This research was duly supervised by Dr. G. Sharma and Mr. K.T. Akindeji at the Durban University of Technology.

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DEDICATION

This work is dedicated to:

Almighty God for his grace and mercy,

My encouraging and caring wife; and my children.

&

In loving memory of my deceased mother

ACKNOWLEDGEMENTS

Gratitude to Dr. Gulshan Sharma for providing motivation and knowledge and my Co-supervisor, Mr Timothy Kayode Akindeji for assistance during the journey of my study.

Thankful to Prof. I. E. Davidson and my friend Dr. Ojo Evans for providing the necessary resources to make my postgraduate studies a success.

ABSTRACT

Renewable energy in particular solar energy is a viable option to meet the increasing energy demand for the modern world. The Solar resource in South Africa is among the highest in the world. With the progression of modern society, both energy demands and energy prices are increasing, which has welcomed the introduction of renewable energy resources as an alternative. However, solar radiation varies over the complete day sometimes over the season, and sometimes over the complete year. Further, the power demand is highly variable in nature. Hence, the generated power should match the customer demands over the period of twenty-four hours, and further, it should be economical for customers and electrical utilities. Hence, this study will focus on integrating PV plants with thermal plants to meet the rising customer power demand. The integration of PV with thermal power plants will bring some new challenges in the domain of power system operation & control which is the frequency of the power system should be restricted to well-defined values. Hence, suitable control strategies are to be developed for the successful and smooth operation of the power system. In this research work, an attempt is made to investigate an interlinked system comprising of a thermal and a PV generation system. The control strategies based on PID controllers and their gains tuned through effective tuning techniques are presented. In addition, the concept of fuzzy logic is used to address the problem of frequency managing of PV-Thermal via effectively designing fuzzy proportional, fuzzy integral, and fuzzy PI built control strategies to ensure the frequency regulation of the energy system. The obtained results are shown via a graphical approach, and the best control design is explore and suggested for the considered system. In addition, the scope for further improvement and possible direction areas are also explored and listed in this report.

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ABBREVIATIONS

ACE	Area control error
AGC	Automatic gain control
AI	Artificial intelligence
ANN	Artificial Neural Network
AT	Ambient Temperature
BP	Back-propagation
DCC	Directional Converter Control
HRES	Hybrid Renewable Energy System
HSCS	High-level Supervisory Control System
LFC	Load Frequency Control
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
PID	Proportional-Integral-Derivative
RES	Renewable Energy Sources
RF	Renewable Fraction
RMSE	Root Mean Square Error
SI	Solar Irradiance

CHAPTER ONE

INTRODUCTION

1.1 Background and Motivation

The use of renewable energy sources for electrical power generation is on the increase these days. This due to the fact that the fossil fuel reserves are diminishing. Renewable energy such as solar, wind, tidal, biomass, etc., due to their increasing level of penetration into the power grid, the power system is becoming more complex [1]. In modern power systems, frequency control is more complex due to the characteristics unique to the various power sources interconnected and hence the control is the action of ordering, limiting, or ruling a system in order to obtain a desired response or output. Every system has a control response responsible for its actions, and a control system is an interconnection of components that will provide the desired system response or output [2]. As a result of the rapid industrialization in the world, the energy demand is constantly increasing.

Challenges with storing electrical energy with high capacity promote a practice that the power produced and consumed energy should always be equal. Interconnected power systems are used to mitigate load demand increase in which there is a bidirectional flow to balance the demand and supply of power as a function of time. To keep an interconnected power system operating optimal, the power consumed and the power produced must be equal [3], [4]. To transfer the power, the frequency value should be between 49.2Hz and 50.8Hz. Currently, a variety of load frequency techniques have been explored to optimise load frequency variation. Literature suggests that interconnected power system frequency can be regulated by standard controllers, i.e., PID and fuzzy logic controllers [1], [5], [6]. To enhance the limitations presented by the classical frequency controllers, these days, researchers use the application of artificial intelligence (AI) such as fuzzy logic (FL) [7-12] in order to solve the frequency normalization studies in a more efficient manner. The FL applied to a wide variety of practical control off robot [13], warm water [14], heat exchangers

[15], power system and nuclear reactor [16-17], etc. In addition, the Photovoltaic (PV) system is identified as an important part of the energy balance in the power system in order to cater to the future electric demand in a cheaper and cleaner way. This best concept is to build power generation via PV in the control zone with conventional thermal plant resulting in a linked PV-thermal system and interlinked through AC tie-line. Thus, also presented in this study is the dynamics of frequency of the interlinked system for variable loading conditions. The various configuration of proportional, integral, and proportional-integral fuzzy logic built controllers are designed. These controllers are compared to see which controller yields the best results in terms of normalizing the system frequency after being subjected to a disturbance. In addition, to the present date, the industry professionals are comfortable with PID designs as these actions are simple and easy to understand. Nevertheless, effective gains play an important role and that is why the gains of PID are obtained via tuning techniques and checked to see the best model of PID for frequency managing of PV-Thermal.

1.2 Problem Statement

Power system frequency disturbances have been experienced by many countries in the past between 1970`s to 2000`s. This prompted rigorous research in the area of power system frequency instability issues [18]. The modern power system is dynamic, and frequency stability mitigation techniques are ever-improving.In power systems, the main operation is the Load frequency control (LFC). The operation of the load frequency control is to maintain the balance between interconnected areas in terms of power and also to control the power flow in the tie-lines. This concept is very important for the effective management of the modern power system. The merge of conventional and renewable energy, i.e., PV, has necessitated controller enhancement, and hence it needs further investigations.

1.3 Research Aim and Objectives

The main aim and objective of this thesis is to develop a linear transfer function model of interconnected PV and thermal based power system. Based on this, the goals of the study will be achieved:

- The interconnected power areas joined from side to side AC tie-line will be model and analysed.
- To evaluate the performance of the system for sudden change in the power demand.
- To propose and analyse the architecture of various conventional controllers and to find gains of control through tuning technique that can be used to maintain the balance between the generated electrical power and load demanded by the customers.
- To propose architecture of control strategies based on the concept of fuzzy such as fuzzy proportional, fuzzy integral, and fuzzy PI for solar-thermal system and then use these control strategies to evaluate interconnected power system performance for the sudden change in the customer power demand.
- Based on analysis of the results, an optimum design control mode is proposed that can return the frequency and tie-power fluctuations to its original value in the shortest time after being subjected to step load variations.

1.4 Research Methodology

The novelty of the proposed scheme is that the interconnected power systems project will be done using the following methods. Firstly is the analytical analysis, and this entails the modeling of the linked PV-thermal system. The modeling and analysis involve the development of the transfer functions that will be used to carry out the analysis of frequency control of the power systems. Secondly is the numerical analysis, and this concept will be implemented in a computer program such as MATLAB/Simulink. The computer simulation, based on the results obtained, the dynamic frequency control of the power systems will be evaluated.

The following processes will be used to implement the research methodology in order to achieve the thesis aims and objectives are as follows:

- Conduct an extensive literature review of LFC strategies and application.
- Develop transfer function model for PV-thermal power system.
- Design models of PID and Fuzzy oriented controllers and apply to joined system model.
- Evaluate the performance of the model for sudden change in power demand.
- Simulate the performance of the interconnected model using MATLAB/Simulink and to analyses the results.

1.5 Thesis Outline

This dissertation consists of six chapters. The layout for these chapters are briefly discussed as follows:

Chapter 1: Introduction: This chapter was used to discuss the general background and motivation as well as the problem statement and the aims and objectives of this study. Also presented in this study is the discussion of the research methodology.

Chapter 2: **Literature review**: This chapter was used to discuss the research that has been done on this topic. This entailed the concepts in general, and the various algorithms used to develop controller and the application specifically to interconnected power systems about frequency control.

Chapter 3: Design and application of PID Controllers: This chapter was used to present the first concept of the research methodology**.** This methodology involves the design and the mathematical modelling of a solar-thermal interconnected power system. This chapter also includes the design of various models of PID and gain design over and done with tuning methods.

Chapter 4: Design of fuzzy-oriented controllers: This chapter was for the second research methodology. Design, computer simulation and analysis on the basis of different architecture of fuzzy controllers for stable operation of PV-thermal interconnected power system.

Chapter 5: Results analysis: This chapter was used to present the analytical and the graphical results. These results were obtained from the formulation and implementation of the two methodologies (simulation results from chapter 3 and 4) used in this study in the MATLAB environment. These results were analysed, discussed, and comparisons were made. Finally, inference was made based on the analysis of the most adequate mode that can be employed for frequency control.

Chapter 6: Conclusions and recommendations: In this Chapter, the conclusion of the study was made, and future recommendations on possible areas for further research work are provided.

1.6 Publications

The publications below are materials forming part of this dissertation;

1. M. S. Estrice, G. Sharma, K. T. Akindeji, and I. E. Davidson, "Frequency Regulation Studies of Interconnected PV Thermal Power System," in 2020 International SAUPEC/RobMech/PRASA Conference, 2020: IEEE, pp. 1-5.

2. M. Estrice, G. Sharma, K. Akindeji, and I. E. Davidson, "Application of AI for Frequency Normalization of Solar PV-Thermal Electrical Power System," in 2020 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD), 2020: IEEE, pp. 1-4.

CHAPTER TWO

Literature Review

2.1 Introduction

This chapter presented the main concepts as found in literature of grid-connected PV systems with regard to modern power systems. Power systems usually consist of three aspects: generation, transmission, and distribution. These aspects of the power arrangement are set out to achieve continuous power with voltage stability. But because of undesirable disturbances that may arise for one or more generators, this will impact negatively on the entire system resulting in an imbalance in power between the generation and the demand. An electric power system is constituted of several elements, e.g., generators, transformers, power transmission lines, distribution networks, and loads as well as control elements, e.g., automatic voltage regulators, load frequency control mechanism, protective relays, and circuit breakers. This equipment can be considered to be made up of linear impedance elements of resistance, inductance and capacitance. The study of the control of modern power systems is required in order to run the system economically and maintain a continuous balance between generation and varying load demand. [19-21]

To be reliable, the system must be secure, and to be secure, it implies that the power system must be stable. The power system must be kept at the optimal level in order to permit maximum power delivery. [22]

Power system analysis entails comprehending the working of the power system as a unit. The analysis is done by assuming the system in the steady-state mode, alternatively during dynamic fault condition mode. Under normal conditions or steady-state conditions, the average electrical speeds of all generators remain the same throughout the system. To achieve steady-state condition, the input mechanical torque must equal the output electrical torque per machine of the system, and this is termed synchronous operation of the system. A balance between energy supplied and energy required is essential for stable power system operation. [20, 23, 24]. System stability is defined by the time it takes, after the system has been subjected to a fault, to return to it`s steady-state mode. The foremost prompt dangers of synchronous operation of a control framework are the high transient mechanical torque and currents that more often than not happen. To anticipate these drifters from causing mechanical and thermal loss, synchronous engines and generators are nearly prepared with pull-out protection. The control is autonomous, and each area is responsible for its own steady state power balance. The problems of dynamic, transient stability, steady state stability, and voltage and frequency regulation, power optimization need to be properly analyzed and on the other hand a methodology of the overall system control to be devised [19, 23, 25, 26].

2.2 Control Systems

In a control system, the output signal measurement is used for feedback signal. An error flag is created when a reference flag is compared with the input flag. The error flag is at that point bolstered into a controller to deliver the system`s control input as appear in figure 2.1. The controlled system can be in the form of a manufacturing plant, power plant. As illustrated in Figure 2.1, the control systems components consist of transfer functions for the controller $K(s)$, that actuator $G_a(s)$, the plant $P(s)$, and the sensor $G_m(s)$. In this control system, the disturbed output of the plant is $y(t)$ and its noisy measurement is $y_m(t)$, is corrupted by the measurement of noise $n(t)$. The error between the desired output $y_d(t)$ (or reference) and the disturbed out $y_m(t)$ is the measured error $e_m(t)$. The actual error between the plant output and the reference can be evaluated by [7]

$$e(t) = y_d(t) - y(t) \tag{2.1}$$

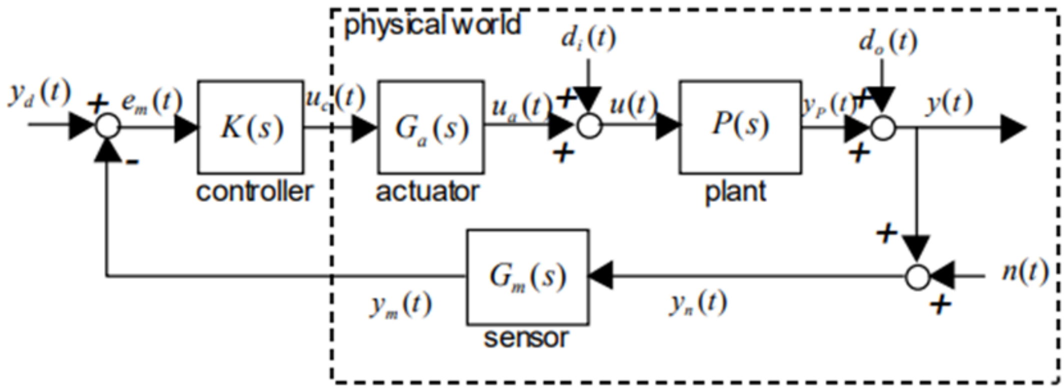

Figure 2.1: Typical Transfer Function Block Diagram of a Feedback Control System [7]

The output disturbance is the signal denoted by $d_o(t)$, the output measurement noise is denoted by $n(t)$, and the feedback measurement sensor dynamics are modelled by $G_m(s)$. The actuator $G_a(s)$ (e.g., a valve) is used to modelled the device that translates a control signal from the controller $K(s)$ into action on the plant input. [25]

Feedback in control systems ensures that output signals and the reference trajectories are maintained close to their set point. In line with this objective, the benefits of feedback control systems are:

1. To neutralize unsettling disturbance signals influencing the yield i.e., output.
2. To stabilize an unstable plant.
3. To enhance system delivery in the presence of model uncertainty.

2.3 Renewable Energy Integration

The demand for electrical energy is increasing at an exponential progression, while power generation is increasing at an arithmetic progression. In this way, for future requests, the existing era frameworks will not be able to supply the loads. Therefore, this has become an important issue which is there is need for alternative energy sources for power generation has. This slant focuses on creating clean and eco-friendly green energy that can contention the thermal and nuclear power stations. As a response to this need, there are numerous research studies being carried out in the area of renewable energy resources such as wind power generation, tidal and solar energy to supplement the traditional energy sources such as fossil fuel. This is necessitated because of the rapid depletion of fossil fuels coupled with environmental damage such as global warming caused by plants that use fossil fuel has led to a global. In this vain, utilize of green energy can have a driving part in democratized energy generation and utilization in any nation. It is commonly known that out of all the renewable power sources, sun-oriented vitality has the slightest effect on the environment. Power delivered from photovoltaic (PV) cells does not result in natural contamination, drain normal assets, or imperil living creatures [28]. For numerous a long time, the centralized grid has been one way of power stream, created by expansive, inaccessible control plants and disseminated over huge separations by transmission lines to homes and businesses. In later a long time, the system's deficiencies are expanding, leaving the consumers with the burden of outsourcing energy from other forms of energies for survival. The traditional grid highly depends on planet-warming fossil fuels. Due to the massive production of harmful greenhouse gases as a result of the burning of these fossil fuels, the traditional way of producing power seems to be doing more harm than good and is slowly being replaced by new non-conventional such as renewable. Most renewable energy sources are mostly used for Micro grids as an Island power generation. These days, there is the need for the integration of REs into the national grid, and this concept is rising rapidly.

The integration of these REs will be most beneficial to the countries like South Africa national grid, which is not only responsible for supplying local consumers but has neighbouring countries that rely on the same grid for energy security. RE integration is most crucial for such a heavily burdened utility. However, such injections into the grid may have negative impacts on the power system, causing system instability and possibly, failure. This is why it important to understand what a stable power system is, the risks or "side-effects" of RE integration into the grid, and look at possible ways to mitigate these risks, which will result in a stable, efficient, reliable, and secure power system.

2.4 Impacts of Renewable Energy Integration upon the Grid

The uncertain nature of renewable energy sources brings new challenges when integrated into the grid network. Energy production and conversion losses are experienced. Hence, the sum of total power depends on the amount of RESs being utilized over a period of time [22]. Power generation and utilization must be kept in balance to maintain a strategic distance from conflicting power generation to power estimating and arranging. [31]. The nature of modern power grids is susceptible to reverse power flow. The challenges presented with the integration of renewable energy sources into the current grid are discussed as follows.

- Power Stability and Quality

The system stability is the capacity of the framework at given an starting state to recapture a state of balance after being subjected to a physical disturbance, with the state-variable being bounded and the framework essentially operational. The stability of the system is classified into three categories to be specific, angle, voltage, and frequency stability. Power quality in the first instance is a function of frequency and voltage. Parameters such as harmonic content, transient voltages, and current, service continuity, and variation in frequency and voltage amplitude are used to define power quality. Customer equipment failure or malfunctioning are due to poor power quality resulting from the distortion of waveform shapes of current and voltage. [32, 33]. Significantly, high penetration of RESs in a power system may result in numerous power quality issues [34]. For instance, power quality problems that may be introduced by PV power systems are variation in solar radiation, cloud shadows, and power electronic apparatus like inverters and filters [31]. In the case of wind energy, problems may be introduced by wind speed variation, power electronic devices, and errors due to misalignment between turbine facing direction and wind direction. Problems introduced by power electronic interface may include harmonic injection, inrush currents, decreased grid damping due to non-linearity and resonance phenomena. Problems introduced by fluctuating nature of energy sources are as follows, voltage fluctuations, voltage unbalancing, deviations in frequency, and over voltages during fed-in. Further, problems may include voltage spike, voltage swell, under-voltage, over-voltage, voltage sag, voltage interruption, and voltage flicker. [35, 36]

- ❖ Reactive Power Compensation Capability

Induction generators of type A and type B used in wind turbines rely on reactive power. These turbines are fixed speed and limited variable speed, respectively. If the system experiences imbalances in reactive power, issues such as voltage instability, which give rise to voltage drops in buses and lines, may occur, exposing the system to failure. Sufficient and well-controlled reactive power yields other benefits such as minimum losses in Solar PV power system. These make the control of reactive power an important aspect of RE integration and beneficial to obtaining a stable and operational multi-source power system.

- ❖ Point of Common Coupling (PCC) and Voltage Level

The PCC is understood to be the point where the micro grid is joined to the utility in the electrical circuit that is an electrical point where multiple generators and loads are connected. According to IEEE Std. 519 access to the PCC must be available for direct measurement for consumers and the utility. The uncontrollable and unpredictable characteristic of RESs causes variations that result in voltage variation at the PCC. The short circuit faults a grid can mitigate at the PCC without overall system interruption is used as an indicator of grid strength [22].

- ❖ Frequency Instability

The frequency of the system serves as an essential marker for the sense of balance between the overall generation and the overall load within the power system. When a generation/load lop-sidedness unsettling disturbances happen, the synchronous generator will infuse or absorb energy into or from the power system to neutralize the awkwardness, changing the frequency [19]. Synchronous inertia in control frameworks is the pivoting mass of generators synchronously associated with the network. The speed of rotating masses will change if the instantaneous supply is not equal to the demand. Non-synchronously connected power sources such as REs and HVDC interconnections are unable to provide inertia naturally to the power system because the power they inject into the grid passes through inverters (Power Electronics) before reaching the loads. Therefore, the penetration of REs into the grid result in frequency instability due to the less synchronous power generators on the network, which influence the rate of change of frequency (RoCoF) [38]. Frequency instability in a power system can disastrous; it brings about voltage fluctuation, system power quality issues, and overall system instability. As a result, of these negative impacts, numerous control systems have been developed as a means to counteract the unavoidable issues brought about by RES.

2.5 Application of Controls in RE Systems

The effectiveness of a power system and the quality of the yield control can be incredibly improved with the utilization of control elements. They are closed-loop input frameworks coordinates into active power conversion stages to control the switching elements. Controls can be found in various places throughout the power system. Control systems used mostly to achieve flat voltage on the DC link, which will decouple the grid from power variations due to RE fluctuations, in RE applications [39]. With the utilization of control system the yield (output) control can be utilized to oversee output active & reactive power for a full power factor correction approach [22]. Additional action can moreover be presented to oversee the power storage system. The storage cells will interface through the capacitor bank, requiring a DC/DC transformation and controls system, maintaining the voltage regulation when the RESs are in excess and overproducing power, and ensuring the proper power delivery during low RESs situations [39]. The use of RESs has its benefits and severe negative effects on the power system. However, the benefits prove to be greater than the negative impacts. Based on this, several researchers and several engineers have focused their research on new control techniques that can be used to control and manipulate RESs to produces efficient and quality power with minimum risk factors.

This project looks at the commonly used control systems for frequency and voltage control techniques in RE integration into the national grid. Since frequency stability is an important aspect of an effective power system, controlling the frequency eliminates most of the system instability problems [41]. The commonly used control systems for power systems are discussed in the next three sub-sections.

2.5.1 Droop Control

Droop control strategy is the foremost utilized strategy for controlling the integration of REs (micro grids) with the grid, working in parallel to share the overall load request agreeing to their particular evaluations to avoid distributed generation (DG) over-burdens and to guarantee steady operation of the micro grid. The original frequency and voltage droop strategy permits the DG units to share the load request without physical communication among them by imitating a conventional control framework with parallel synchronous generators. Figure 3 shows the original droop control system block diagram which has been developed over the years to match each micro grid it has to control [24].

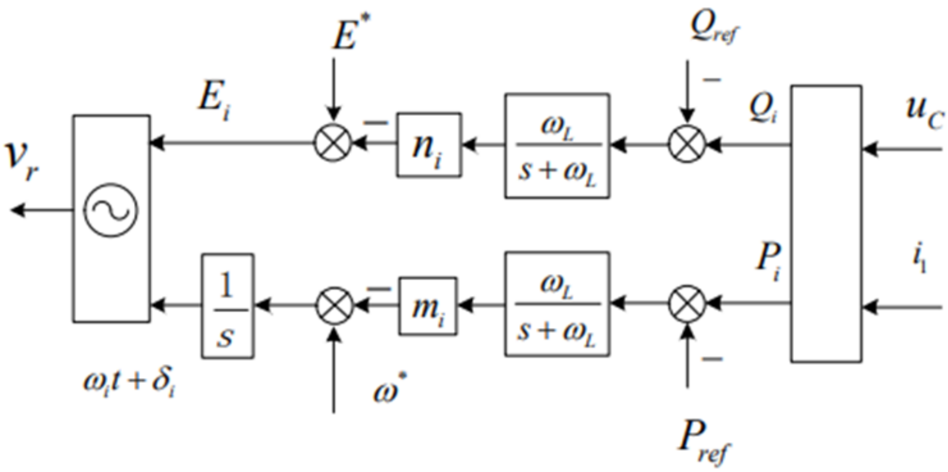

Figure 2.2: The Droop Controller [25]

where, E^* and $\omega^*$are referenced values of voltage amplitude and angular frequency, respectively. m_i and n_i are droop coefficients. P_i and Q_i are output active and reactive power of the inverter. P_{ref} and Q_{ref} are their referenced values. ω_L is cut-off frequency of low pass filter, which reduces ripples of calculated values of P_i and Q_i. The equations for the control block diagram in Figure 2.2 can be written as [25]:

$$E_i = E^* - n_i(\mathrm{Q}_i - Q_{ref}) \tag{2.2}$$

$$\omega_i = \omega^* - m_i(\mathrm{P}_i - P_{ref}) \tag{2.3}$$

$$\omega_i t + \delta_i = \int(\omega^* - m_i(\mathrm{P}_i - P_{ref}))\,\mathrm{d(t)} \tag{2.4}$$

2.5.2 Robust Droop Control

A robust droop controller can be viewed as an enhancement of the droop controller [44]. The robust droop control is represented in figure 2.3 as follows; V is the amplitude of the terminal voltage u_C. K_e is the again coefficient. Other symbols have the same meanings as in Figure 2.2. The robust droop controller takes inverters terminal voltage V into consideration and imports an extra integrator in voltage V and reactive power Q_i part [26]. This not only increases The accuracy of power-sharing when multi-inverters work in a parallel way is increased, and a reduction in the fluctuations of the drive signal v_r is observed. Compared with the original droop controller, it's easy to find that they are similar in $P-\omega$ part and different in $V-Q_i$ part, is similar to that presented in equation (2.2) [25]:

$$E_i = \int[K_e(\mathrm{E}^* - V) - n_i(\mathrm{Q}_i - Q_{ref})]\,\mathrm{d(t)} \tag{2.5}$$

Therefore, equations (2.3) to (2.5) are the mathematical equations that can be used to describe the robust droop controller.

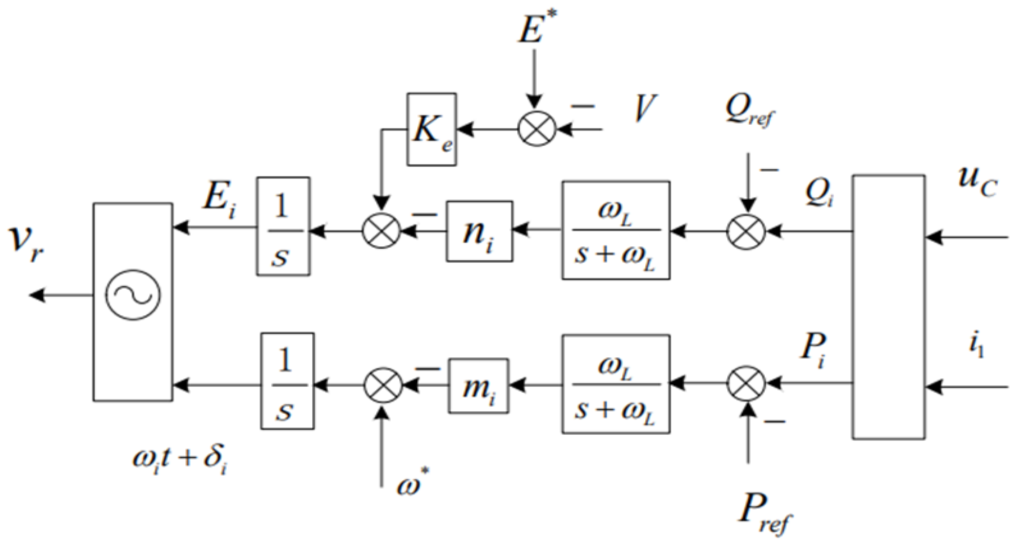

Figure 2.3: The block diagram for Robust Droop Controller [25]

2.5.3 Virtual Synchronous Generator (VSG) Controller

There are several VSG schemes that are used for control. They are one concept in common which is that they introduce synchronous generators (SG) rotor swing equations to slow down change speed of phase of pulse width modulation (PWM) waves. That is why the VSG has so-called virtual inertia, and this benefits system frequency stability. There are some VSG controllers that take a double-loops structure [45, 46]. As practice power loop is taken as the outer loop, and current loop is taken as the inner loop. There are other VSGs that only have outer power loop. For simplicity, because the inner current loop always has a much faster response speed than that of the outer loop, when analysing the system stability or low-frequency oscillation, it is reasonable to ignore the dynamics of the inner loop. Figure 2.4 shows the basic single loop VSG control system block diagram, which is the basis for a lot of improved VSG controller designs [43].

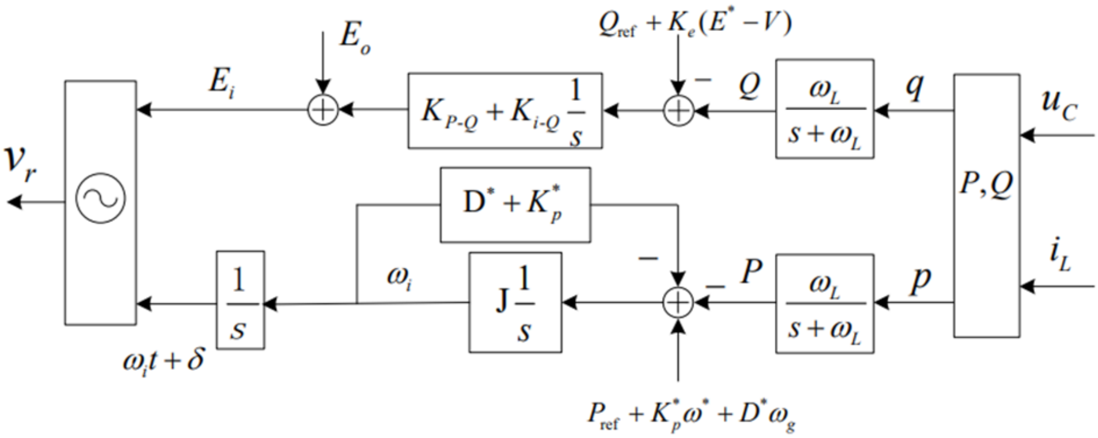

Figure 2.4: The block diagram for the VSG Controller [25]

where E_0 is a feed-forward component which can speed up dynamic response for the VSG to regulate its terminal's voltage. K_{P-Q} and K_{i-Q} are control parameters of PI (proportional-integral) controller which acts on $Q-V$ part of the VSG. K_P^* is a droop coefficient of $P-\omega$ part, similar to m_i as shown in Figure 2.2 and Figure 2.3. Value of $1/J$ means virtual inertia, which directly effects the inverter's output power response speed. ω_g is micro grids' angular frequency. D^* is the damping coefficient, and there a benefit of having higher damping if sets at a proper value? Other symbols have the same meanings as shown in figures (2.2) and (2.3). For the VSG controller, as shown in Figure 2.4, the mathematical equations can be written as follows [29]:

$$E_i = E_0 + (\mathrm{K}_{P-Q} + \frac{1}{s}K_{i-Q})(\mathrm{Q}_{ref} + n_i(\mathrm{E}^* - V) - Q_i) \tag{2.6}$$

$$\omega_i t + \delta_i + J \times \int \frac{P_{ref} + K_P^*\omega^* + D^*\omega_g - P_i}{s+T} d(t) \tag{2.7}$$

Where, $T = J \times \left(D^\bullet + K_p^\bullet\right)$. This means T is a design parameter and has nothing to do with the parameters of the electric circuit.

2.6 Concept of Power System Stability

Power system stability may be characterized as that property of the control framework that empowers it to stay in a state of working in harmony beneath typical working conditions and recapture a satisfactory state of harmony after being subjected to an unsettling disturbance. Stability research are conducted when modern generating and transmitting facilities are arranged and is a very important aspect in order to guarantee a reliable supply of power. Power system stability ensures that the operation of the system is within the specified limits of voltage and power angle during normal and abnormal changes in operating conditions. It ensures that the operating point remains in equilibrium position despite slow, steady, or abrupt changes in operating conditions. The load on the system may alter slowly or abruptly. Sudden changes of the load may be due to speedy exchanging operation or sudden faults taken after by tripping of lines etc. stability studies about are accommodating in deciding the nature of the protection required, basic clearing time of circuit breakers, voltage level of and exchange capability between control frameworks. There are two main methods for analyzing the transient stability of the power grid system

a) Direct Methods: This method is used to analyze the transient stability by the direct calculation of the reserve or limit of transient stability.
b) Simulation Methods: This can be the foremost visit strategy for assessment transient stability. This method has to do with the time simulation of the previous event i.e. resolution of the system using non-linear differential equations using numerical integration methods. This simulation strategy is a coordinate method serve to confirm both the solidness of a single generator as well as the solidness of the complete and portion of the electrical framework. Transient stability studies using simulation can be solved using the following:
    - Time Domain Simulation for a specific disturbance that at each time point involves a solution of algebraic solutions representing the generator and sometimes the load dynamics. Simultaneous in which

algebraic and differential equations are solved or alternately solving both.

- Simulations of pre-disturbance, disturbance, and post-disturbance computations are performed. The program outputs include: power angles, frequency of synchronous machines, bus voltages, and power flow versus time

2.7 Power System Stability

Power system stability as captured by IEEE/CIGRE Task Force [47] as, “the ability of an electric power system, for a given initially operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance with most system variables bounded, so that practically the entire system remains intact”. Power system stability issues has attracted the attention of researchers [48] [49 [50]. The evolving and complexity of power system networks and operation there of introduces additional stability issues, for example, the problems associated when renewable energy is part of an interconnected power system [52] [53]. Steady-state stability and transient stability can be broadly termed as the two categories for stability analysis for an electrical system. For each working condition, the behaviour and severity of the possibilities of the contingencies of electrical framework will be diverse. More often than not, the control framework is modified so that the post-disturbance operation contrasts from that earlier to the unsettling disturbance. In this manner, when the electrical control framework stabilizes, the unused consistent state working condition will be diverse from the past one [53].

2.7.1 Power System Operating States

The five working states of the control framework is spoken to in Figure 2.5. As reported in [54], within the ordinary state (normal), the framework works in a steady state. The framework advances to the alert state in case the framework factors drop underneath certain criteria but still inside satisfactory parameters. The emergency state mode is enacted in case the framework is incapable to moderate any possibility due to over-burden. In case there's an escalation with the seriousness of the disturbance, the framework enters extreme (or extreme emergency) state. The restorative state is when the control activity is lock in to reconnect all facilities and re-establish framework loads.

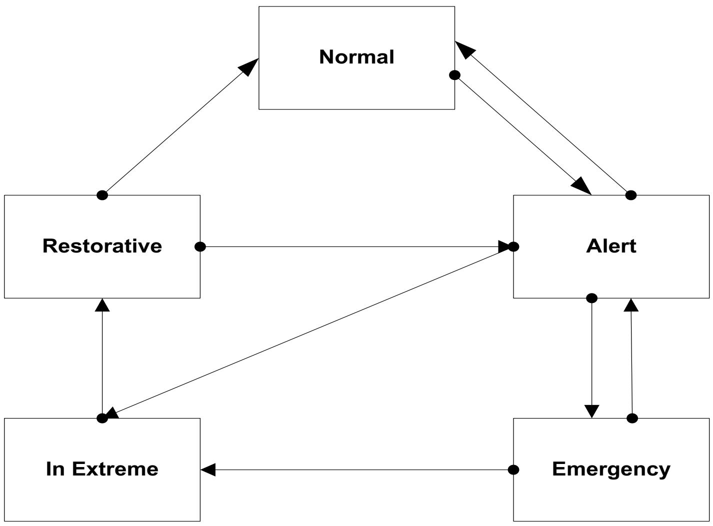

Figure 2.5: Operating States for Electrical Power Systems [54]

2.7.2 Load Frequency Control

Load-frequency control (LFC) in power system is crucial for the conveyance of electric energy with abundant quality. The point of LFC is to preserve zero steady-state error in a multi-area interconnected system. In expansion, the power system ought to fulfill the dispatched conditions. A part of studies has been made within the past within the range of load-frequency control in interconnected systems. Within the writing, a few control methodologies have been recommended based on ordinary straight control theory i.e., conventional controllers. However, linear control strategies are not desirable for the application of power systems because of its high non-linear characteristics. Hence, the gain scheduling controller can be utilized [55]. This technique best fits non-linear systems. In this strategy, the control parameters can be changed exceptionally rapidly since parameters estimation isn't required.

2.7.3 Frequency Stability

Frequency stability is reliant on keeping a balance between generation and consumption with the least loss of loads. Therefore frequency instability is a result of electrical power deficiency [56]. The interconnected regions can be commonly related by splitting the regions into islands with distinctive capacity of power generation and certain loads. Frequency regulation may be an exceptionally imperative issue in isolated island grids as these islanded grids come across various severities of disturbances such as misfortune of power generation or loads [57]. The classification of power systems helps to understand the approach to mitigate frequency stability problems. Frequency stability displayed in Figure 2.6 sorts power system stability into short–term and long– term phenomena:

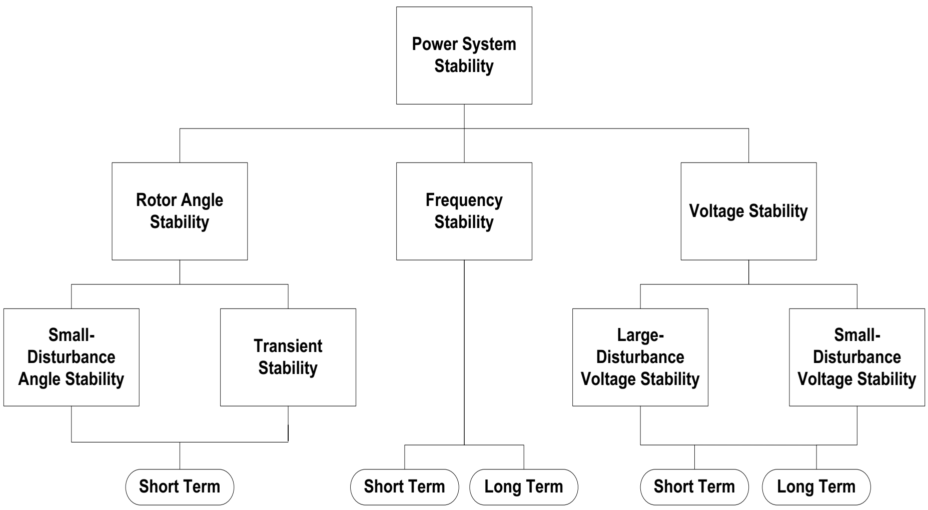

Figure 2.6: Classification of stability based on the IEEE/CIGRE Task Force

The quantity of electrical power generated by power systems is mostly generated by synchronous generators. The system frequency is sustained by the synchronous generators [58]. The power supplied and the load demand must be kept in balance [59]. Keeping the balance between power supplied and load demand will ensure that the system frequency remains stable. System frequency will increase if power generated is more than load demand, and system frequency will decrease if power generated is less than load demand. The frequency must be restricted within maximum and minimum alteration limits in order to have grid failure, and it can also cause a serious threat to equipment [58] [60].

2.8 Power Frequency Control

For a power system to operate in a stable state, the system frequency and voltage must function within the steady-state parameters. Due to the varying load on the power system, the system frequency is not constant. Power deficiency is experienced if there is a difference between the power produced and the power consumed. Managing the generator speed is one of the methods employed to control system frequency. A governor is employed to monitor and regulate the generator speed. Inertia provided by the generators normally takes care of the initial increase in load demand. As this increase in load, demand is being dealt with, the generator speed decreases, and as a result, the system frequency also decreases. In the case of interconnected power systems, frequency management is achieved with controllers to recover system frequency during contingencies conditions. Figure 2.7, explains control requirements to bring back original frequency for various operating conditions.

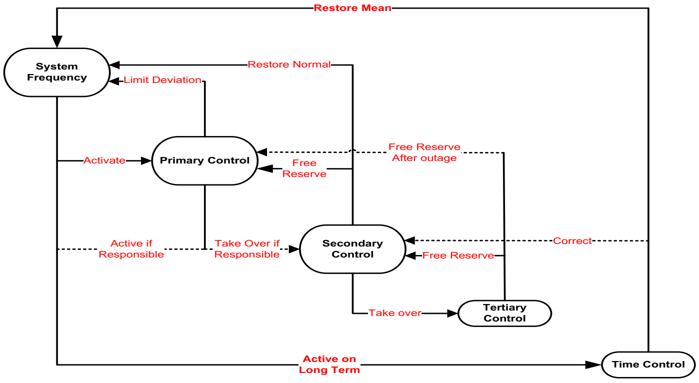

Figure 2.7: Frequency control in power system [61]

2.8.1 Primary Frequency Control

In this control mode, the inertia supplied by the generators is used to address the change in load, and as a result, the system frequency is normalized. [62]. First control action will not return the frequency to its ostensible esteem but will stabilize the system frequency. The gain of the feedback system within the first frequency controller is called droop Auxiliary and tertiary levels controllers and are utilized to reestablish frequency to its ostensible level (50 Hz) [63]. Generator governors have a dead band region normally ± 20 mHz in which the primary frequency controller will not be activated [64].

2.8.2 Secondary Frequency Control

The purpose of this controller is to restore the system frequency back to its nominal value and also restore the primary controller for next contingency. This mode of controller is also refer to as Automatic Generation Control (AGC} and is usually activated to restore balance between generation and load. [65].

2.8.3 Tertiary Frequency Control

The tertiary controller is employed when the secondary controller is not able to restore the system frequency to its nominal value. Tertiary frequency response is normally in the form of security-constrained economic dispatch [66]. This mode of control results in controlled load shedding, altering the generator set points, and by altering the power interchange program.

2.9 Power System Frequency Response Time Frames

The frequency response of a power system can be classified into three categories, namely inertial response (IR), primary frequency response (PFR), and secondary frequency response (SFR}. Figure 2.8 presents the relevant time frames involved in each phase of the system frequency response when considering a generation outage.

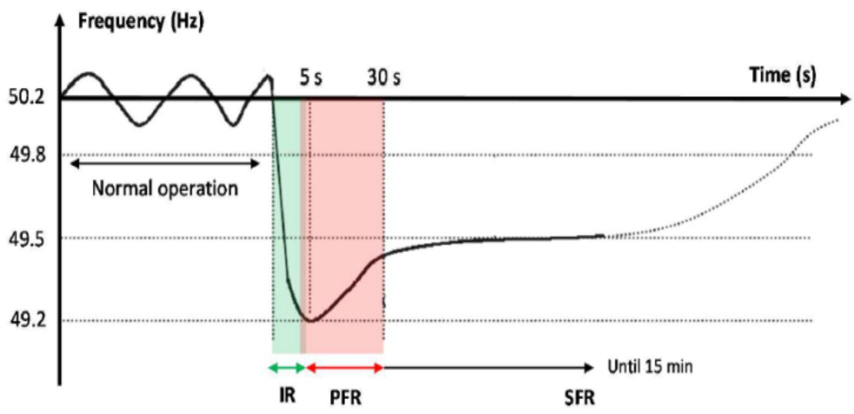

Figure 2.8. Time frames involved in the system frequency response [40]

2.9.1 Inertial Response

After the power system disturbance, a mismatch between input and output power will occur, resulting in the system frequency decreasing governed by the total inertia of the system.

$$H_{sys} = \frac{\sum_{i=1}^{n} H_i S_i}{\sum_{i=1}^{n} S_i} \qquad (2.8)$$

where H_i and S_i are the inertia constant and the nominal power of generator *i* , respectively.

After a power system has been subjected to a fault the kinetic energy of the generators try to compensate for the energy difference between the power generated and the load energy [67]. This contribution leads to a speed reduction of the machines until the rate of change of frequency (d*f*/d*t*) becomes zero [42]. This type of response of synchronous generators is called inertial response.

$$2H\frac{d\omega}{dt} = T_m - T_e \qquad p.u. \qquad (2.9)$$

where *H* is the inertia constant (in seconds), ω is the rotational speed of the generator, T_m is the mechanical torque, and T_e is the electromagnetic torque.

2.9.2 Primary Frequency Control Time Frame

After the dead band period is exceeded, the governors of the synchronous generators respond to increase the generator power. Synchronous generators will hence increment their output until adjust between generation and requirement is reestablished, and the frequency of the power system has been stabilized. This reaction happens in a time outline from 5 to 30 s, depending on the characteristics of the generation units.

2.9.3 Secondary Frequency Control Time Frame

The secondary frequency function is to restore system frequency back to its nominal value and restore primary power reserves. Auxiliary control reserves are engaged in around 30s after a possibility and must be completely operational considering 15 min.

2.9.4 The Need to Keep System Frequency Constant

Listed are the reasons why the system frequency should be kept constant: [68]

- Alternating current motors run at a set frequency, and a variation of the system frequency will affect the motor operating speed.
- The electric clocks are frequency-dependent. Hence the accuracy of the clock will be affected.
- In case the ordinary frequency is 50 Hertz, and in case the frequency falls underneath 47.5 Hertz or goes up over 52.5 Hz it will harm the blades of the turbine.
- Frequency fluctuations are not acceptable for power transformers as this affects the flux in the core.
- The most severe impact of abnormal frequency operation is watched within the case of thermal Plants since the impact of the ID and FD fans within the control stations diminished.

2.10 Fuzzy Logic

Jan Lukasiewicz, a Polish philosopher, invented fuzzy or multi-valued logic in the 1930s. Although classical logic only deals for two values, 1(true) and 0(false), Lukasiewicz introduced logic that expanded the spectrum of true values in the interval between 0 and 1 to all real numbers. In this interval, he used a number to indicate the probability that a given statement was made.

2.10.1 Foundation of Fuzzy Logic

Fuzzy logic starts with a fuzzy set concept. A fuzzy set is a set without a clearly defined boundary that is crisp. It which contain elements that have only a partial membership degree. A fuzzy package of fuzzy boundaries is a set. The validity of every argument becomes a matter of degree in fuzzy logic. It can be any argument any declaration can be blurry. The degree of membership, also called membership value, is expressed by a value between 0 and 1.The behaviour and severity of the contingencies of the operating electrical system would be different with each operating environment. The power system is usually adjusted such that the steady-state activity of the post-disturbance varies from that before the disturbances. Therefore, as the electrical power system stabilizes, the current operating condition of the steady-state will vary from the previous one.

2.10.2 General structure of fuzzy system

A fuzzy inference system (FIS) characterizes a nonlinear mapping of the input information vector into a scalar yield, utilizing fuzzy rules. The mapping handle includes input/output MFs, FL operators, if-then rules, accumulation of output sets, and defuzzification. FIS is shown in Figure 2.9. The FIS maps crisp inputs into crisp outputs. The FIS contains four components: the fuzzifier, inference engine, rule base, and defuzzifier. The rule base contains phonetic rules that are given by specialists. It is additionally conceivable to extricate rules from numeric information. Once the rules have been built up, the FIS can be seen as a framework that maps an input vector to achieve the output.

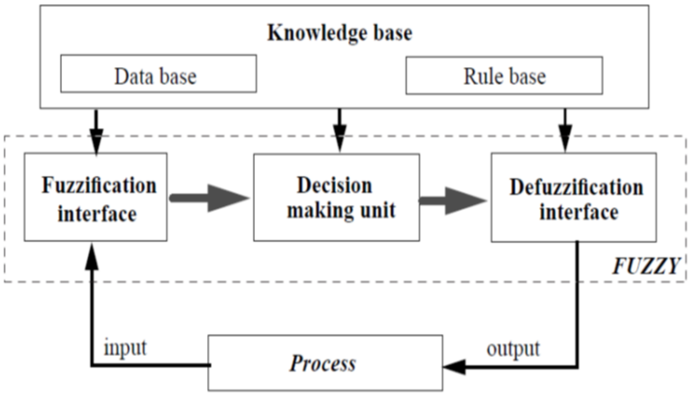

Figure 2.9: Block Diagram of Fuzzy Logic System

2.11 CONTROLERS

As PID is respected as the standard control structures of the classical control hypothesis, and FL controllers have situated themselves as a partner of classical PID controllers on the same prevailing part at the information wealthy range. PID controllers are more pertinent for linear systems. Non-linear systems are effectively dealt with employing fuzzy controllers because of their knowledge-based non-linear structural characteristics. Combining PID controllers and FUZZY controllers provides more effective control opportunities. Various hybrid controller structures have been explored in literature [69,70,71,72,73]. In [74] a fuzzy switch strategy between FL controller and ordinary PID controllers is utilized to realize smooth control between switching.

2.11.1 Brief Review of Classical PID Controllers

Minorsky is generally associated with the modern PID loop. He noticed a helmsman guiding a ship in 1922 and came up with the additive, integral, and derivative method of control that we today know of. Compared to the desired course set point, the control needed to steer the ship based on real ship direction is proportional. Integral is the quantity of mistake that needs to be corrected. For example, if a small amount of the ship is off course, and correcting it to the left puts it back to bearing, then it is improper to turn the wheel all the way to the left. It needs only a minor adaptation to the left. Derivative is the attempt to see how far from the fixed point in the past a method vector (ship route) has been and to predict where the course corridor is. In 1922, Minorsky studied and explored the properties of the three-term controller [63, 65, 66] in his paper on "Directional stability of automatically steered bodies".

2.11.2 Structure of PID Controllers

The proportional-integral-derivative (PID) controller is the foremost routine controller that has been utilized in present-day strategies. As the title endorses, the PID estimation includes three essential modes, and each mode is related with three-time constants as *K*p, *K*i, and *K*d as shown in Figure 2.10. It is generally written in the "ideal form" as:

$$G_{PID(s)} = K_i \left(1 + \frac{1}{T_1 s} + T_D s \right) \quad (2.16)$$

Where K is the proportional gain, K_I the integral gain, K_D the derivative gain, T_I the integral time constant and, TD the derivative time constant.

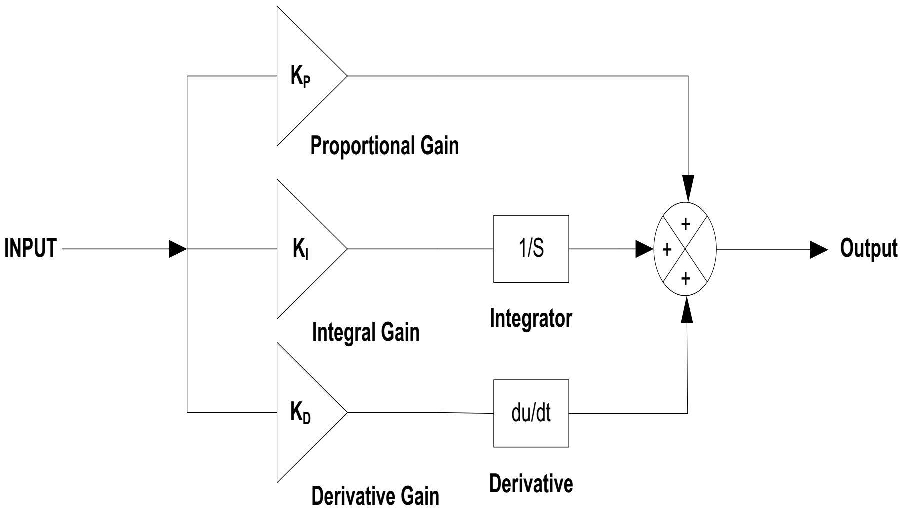

Figure 2.10: Structure of PID control

2.11.3 Fuzzy Logic Controller

Because dynamic features of the power system are complex and variable, traditional methods of control do not provide desired results. It is possible to substitute intelligent controllers with traditional controllers in order to get a fast and nice dynamic response in problems with load frequency control [75]. Fuzzy logic controllers can be more helpful in solving a wide range of control problems if system robustness and reliability are more relevant, as traditional controllers are slower and also less effective in nonlinear system applications [76,77,78]. The Fuzzy Logic Controller is designed to minimize device performance fluctuations [79]. There are several reports on the Fuzzy Logic Controller power system [80,81]. The process variable is held at the reference value by FLC, configured to remove the need for continuous operator attention, and used automatically to change certain variables.

2.11.4 Brief Review of Fuzzy PID Controllers

In the 1990s, to develop the capabilities of classical PID controllers and their relatives, scientists and researchers tried to use intelligent methods, such as fuzzy logic. To achieve behaviour close to that of a standard PID, they attempted to combine fuzzy logic control technology with a traditional PID controller to obtain a regular PID controller. The [82,83,84] thus assumed that a better control system could be accomplished by integrating these two strategies together.

2.12 Hybrid Fuzzy PID Controller Structure

Fuzzy PID controllers in writing can be classified into three major categories as direct action, FL gain scheduling and hybrid type FL PID controllers [85, 86]. The direct action can too be classified into three categories concurring to a number of inputs as single input, twofold input, and triple input coordinate activity FL PID controllers. The classification of FL PID controllers can be seen in Figure 2.11.

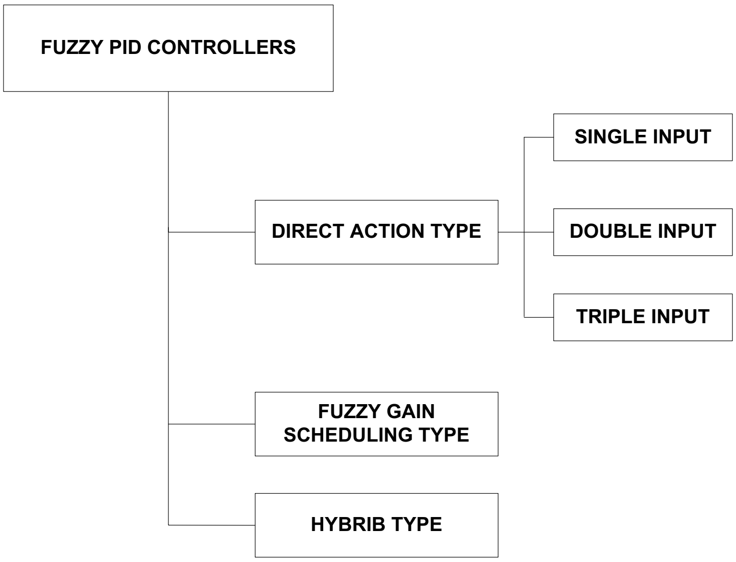

Figure 2.11: Classification of fuzzy PID controllers

In literature, various structures for fuzzy PID (including PI and PD) controllers and fuzzy non-PID controllers have been proposed. A classification of fuzzy controllers is sketched in Figure 2.11. In general, the application of fuzzy PID controllers can be classified into three major categories according to the way of their construction [87,88]. When a typical FLC is constructed as a set of heuristic control rules, control signal is directly deduced from the knowledge base, and the fuzzy inference as it is done in Mc Vicar-Whelan [89] or diagonal rule-base [90] generation approaches [91,92]. Since the fuzzy controller directly drives the process, controllers in this category are referred as “Direct Action” (DA) type [93]. When the picks up of the customary PID controller are tuned on-line in terms of the information base and FL induction, whereas still, the customary PID controller produces the control signal [94, 95], the overall controllers of this category are alluded as “FL Gain Scheduling” (FGS) sort [96]. When a conventional PID controller and a DA type FLC are combined, the overall controllers are referred as “Hybrid” type [96, 97].

2.12.1 Two input fuzzy PID controllers:

If two inputs are used in forming a fuzzy PID controller, then one can obtain either fuzzy PD or fuzzy PI controller. For instance, if the inputs are chosen as error (e) and derivative (or chance) of error, then one ends up with a fuzzy PD controller, as shown in Figure 4. When the inputs are chosen as error (e) and the integral (or the sum) of error, then the controller becomes absolute form fuzzy PI controller. If the inputs are chosen as error (e) and derivative (or chance) of error (e&) then an incremental form fuzzy PI controller can be obtained, but the output is achieved as the derivative (or the chance) of the control signal as shown in Figure 2.12 [98].

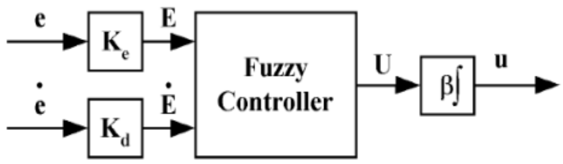

Figure 2.12. Fuzzy PI-type controller structure

2.13 Summary of the Chapter

In this chapter, the problem of frequency managing is explored and investigated and in detail. The problem objectives are framed, and investigations are presented in the preceding chapter of the report.

CHAPTER THREE

Design and application of PID Controllers

3.1 Introduction

Current trends in system security are to maintain constancy and reliability of the electrical power system in order to provide stable, uninterrupted, economical, and quality power supply to the customers. Frequency stability is an important factor to achieve the minimum standards of power delivery to modern society. We achieve frequency stability by balancing power generation with load demand in the electric power system. However, load varies over the period of twenty-four hours. Hence, we install load frequency regulators on the generators in order to keep the generation up or low as per the current system demand. This provides electric power to the customers with minimum variation in system frequency, i.e., ±1% from the standard value of 50Hz, in South Africa.

The frequency stability studies are divided into first and second control action. As there is an unbalance in generation and demand, the initial control action is initiated and tries to keep the generation up or down as per the process of droop mechanism. However, its mode of operation is quite slow, and frequency variations for larger time are not allowed in the electric delivery network, and hence the secondary control actions plays an important role in achieving quick restoration to system frequency to the nominal value. On the other side, in order to achieve highly reliable cost effective network the different power generation areas are linked via AC tie-line resulting into an interconnected network and with the help of these tie-lines, the power can be exchanged between the different power generation areas known as control areas in frequency studies. Further, it is always advisable that each power generation area should meet its own power demand while managing the power exchange over the tie-lines to the schedule value [99,100].

However, due to the variable load demand of the system, the frequency of the system as well as tie-line power fluctuates from the original value, and hence an effective secondary control design is always welcome in the frequency stability studies by the researchers and power engineers. The combination of these two terms in linear analysis is known as area control error (ACE). On other hand, as South Africa is moving ahead in order to meet its current and future power demand through cheap as well as clean sources such as solar power, well known as PV-based power generation, to meet its necessity. However, it is very difficult to achieve the minimum standards of power delivery to customers in terms of confines of frequency and tie-line power as the PV-based power generation is highly intermittent in nature.

Still, the PV-based power generation is the future of the country considering its limitless availability, cost-effective and pollution free keeping the environment of the country clean and disease free as well as in order to cater to the current as well as rising energy demands of South Africa. An initial effort in frequency stability studies is to explore the controller design based on the classical approach [101,102]. However, these approaches prove to be unsuccessful to assorted operating conditions of the energy system. Further, these approaches were tested on interconnected system having the power generation from thermal power plants or hydro-thermal power plants.

The controller design approach for frequency stability studies has advanced over the past few years. Diverse algorithms such as optimal control based on full state feedback [103]; output vector feedback design base on selected states [104], switching structure [105] as well as robust control [106,107] design are applied to achieve the system frequency and tie-line power within its limits by the various researchers all over the world. However, most of the frequency stability treatments are provided for thermal power plants or for interconnected hydro-thermal plants, and very few efforts [108-111] were made in the past to investigate the PV-based power generation and integration to conventional power system resulting in an interconnected network. The PV-based power generation can individually generate electric power and can be considered as one control area. This control area can be connected to other control areas having thermal generation via means of AC tie-line and can participate in meeting the power demand as well as in maintaining the frequency stability for variable load demand of the system.

On other hand, it is noted that power system operators and skilled labor working in diverse control industries are quite aware as well as calm with the diverse structures of proportional-integral-derivative (PID) controllers in order to manage industry operations in day-to-day life in various domains [112]. Though the gains and structure of the controllers is important in analyzing the achieved outputs as well as the stability of the system.

3.2 Modelling of Linked PV-Thermal System

The PV cell have a photovoltaic current source which depends on concentrated of sun based light with diode in parallel to it with a resistance in arrangement having exceptionally moo esteem as appeared in Figure 3.1.

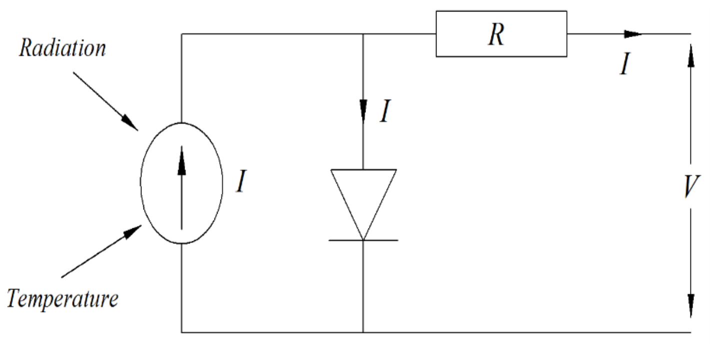

Figure 3.1: Equivalent representation of solar cell

Advance, the sun-oriented board depends profoundly on sun-powered escalated as well as surface temperature. MPPT calculation is utilized to improve the extraction of the greatest control from the sun-oriented board. It is expected for the display thinks about that the sun-oriented radiation is steady with 1000 w/m^2.

The total transfer function (TF) in linear form, including PV panel, MPPT calculation, inverter, and filter, can be spoken to by the taking after condition [112]

$$G_{PV} = \frac{(-18s + 900)}{s^2 + 100s + 50} \qquad (3.1)$$

For the present research work, it is expected that PV is producing power and meeting load demand in control area-1, and thermal power is creating control in control area-2. The thermal framework is having the steam representative to control the stream, re-heater, which increments the productivity of the framework and, at long last, the turbine couple to the synchronous generator. The TF of governor for coal base power plant well known as thermal power in terms of gain (K_g) and time constant (T_g) [99-100];

$$\frac{K_g}{T_g s + 1} \qquad (3.2)$$

The re-heater T_F is as follows with (K_r) as re-heater gain, (T_r) is the time in seconds taken by the steam pressure to cover the time through re-heater:

$$\frac{K_T T_r s + 1}{T_r s + 1} \qquad (3.3)$$

The steam turbine T_F with (K_t) as gain of steam turbine with time of operation in seconds denoted as time constant (T_t);

$$\frac{K_t}{T_t s + 1} \tag{3.4}$$

Lastly, synchronous generator TF with (K_p) as power system gain for thermal power plant and (T_p) as time constant of power system is;

$$\frac{K_P}{T_P s + 1} \tag{3.5}$$

The interconnection of PV with thermal power for frequency normalization studies for load variation in control zone one or in control zone 2 is shown in Figure 3.2. The two control zones are linked via AC tie-line.

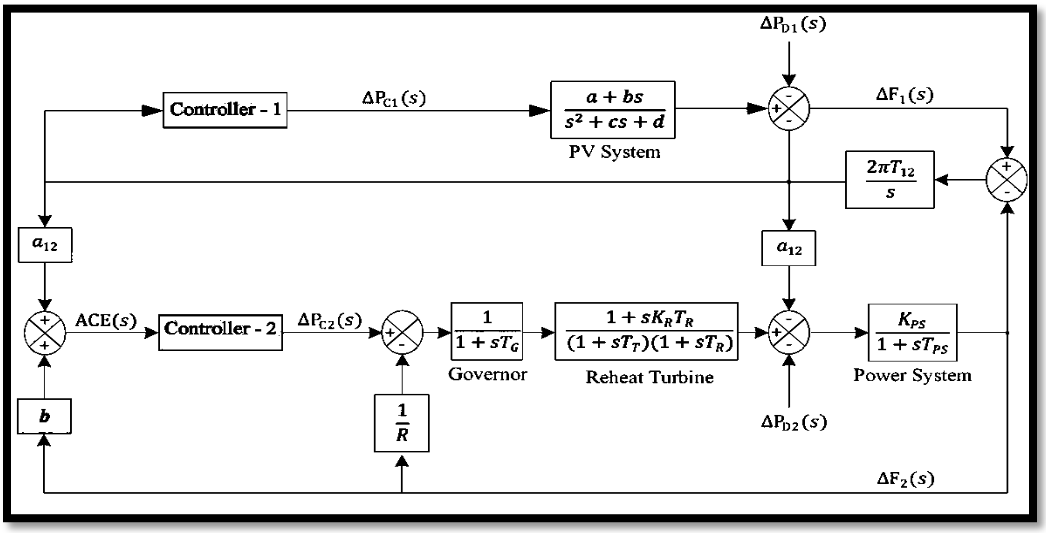

Figure 3.2: TF model of linked PV-Thermal system

3.3 Control Design and Gains Evaluation Modelling

The diverse feature of PID controller is its ability to take benefits of three different control loops known as proportional control, integral control and derivative control in order to achieve the required and optimal output after a certain disturbance. The schematic representation of PID is shown in Figure 3.3. The goal of PID is to calculate the error value, which is the difference between the desired and actual value. Then apply to three different loops in order to adjust the steam flow in thermal power plants as well as to regulate the output of PV to match the generation with power demand in the shortest possible time for variable load demand. The proportional term multiplies the error value with gain K. if the error is large and positive and controller output will be large enough & positive, including the value of gain K. Hence, gain K plays an important role in reducing the overshoot in the system responses. PI alone cannot eliminate the error between actual and desired response, and hence integral loop integrate the error over the time to eliminate the steady state error from the system responses. Finally, the derivate control is applied as it depends on the rate of change of error, and it will help the system to reduce the oscillations as well as to improve the damping effect in the system responses.

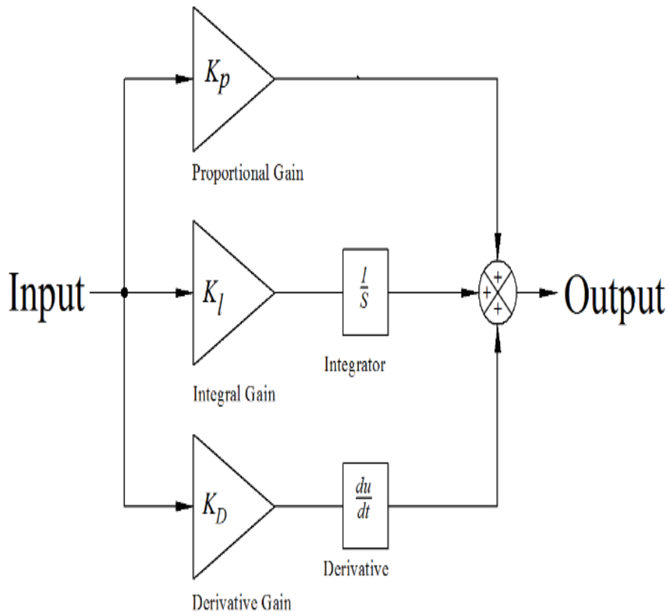

Figure 3.3: The structure of PID controller

Table 3.1 Gains calculation criteria for various PID modes

Controller Structure	Kp (Proportional Gain)	Ki (Integral Gain)	Kd (Derivative Gain)
P	0.5 Ku		
PI	0.45 Ku	0.54 Ku/Tu	
PD	0.8 Ku		KuTu/10
Classic PID	0.6 Ku	1.2 ku/Tu	3 KuTu/40
Pessen Integral Rule	7 Ku/10	1.75 Ku/Tu	21 KuTu/200
Some Overshoot	Ku/3	0.666 Ku/Tu	KuTu/9

No Overshoot	Ku/5	0.4 Ku/Tu	KuTu/15

Finally, the gains of different structures of PID are calculated via different modes. In order to start and to find the starting value for the PID a step load disturbance of 0.01 per unit (p.u.). is applied in thermal power system and increases the proportional gain until the system oscillates as per the Ziegler–Nichols (ZN) method of tuning. The gain after which the system loses its stability is known as ultimate gain (Ku) for thermal power system, and the time between peaks (Tu) is noted in order to calculate the gains of PID for diverse modes using the data given in Table 3.1. The same process is also followed for PV system also. Finally, with the help of Table 3.1 the gains of various modes of PID are calculated and given in Table 3.2 for solar system and in Table 3.3 for thermal power system.

Table 3.2 Gains evaluated for solar system through various tuning techniques

Controller Structure	Kp (Proportional Gain)	Ki (Integral Gain)	Kd (Derivative Gain)
P	2		
PI	1.8	1.5428	
PD	3.2		0.56
Classic PID	2.4	3.4285	0.42
Pessen Integral Rule	2.8	5	0.588
Some Overshoot	1.333	1.9028	0.6222
No Overshoot	0.8	1.1428	0.3733

Table 3.3 Gains evaluated for thermal system using various tuning techniques

Controller Structure	Kp (Proportional Gain)	Ki (Integral Gain)	Kd (Derivative Gain)
P	2		
PI	1.8	2.4	
PD	3.2		0.36
Classic PID	2.4	5.3333	0.27
Pessen Integral Rule	2.8	7.777	0.378
Some Overshoot	1.333	2.96	0.4
No Overshoot	0.8	1.777	0.24

3.4 Summary of the Chapter

This chapter shows the need and integration of PV power with coal power generation resulting in a linked system via AC tie-line. This chapter also shows the model of PV-Thermal in TF approach for frequency studies. Further, it also includes the structure of various models of PID, and the best-calculated gains of PID for various structures of PID for PV-Thermal model is check and analyze for frequency stability studies.

CHAPTER FOUR

Design of fuzzy oriented controllers

4.1 Introduction

Present-day standards with respect to the electricity supply are to deliver consistent and continuous energy to the customer with consistent and unchanged power quality in a safe and secure manner. Frequency robustness is a critical aspect necessary for achieving minimum standards of electricity supply for progressive and developing nations. By creating, an equilibrium between energy supplied and energy required, we maintain frequency robustness. We install frequency regulators on generators since the load duration curve varies over the day. A two-step control process helps to achieve frequency robustness.

Owing to the imbalance between power supplied and power required, the primary control movement first initiates corrective measures to normalize the imbalance through the droop control technique due to the response of the primary control being insufficient and results in delayed correction and frequency deviation for prolonged periods. This is undesirable, and hence, the secondary control responds in a swift action to reestablish the permitted operational frequency. The power control areas are interconnected using the AC tie line, which in turn facilitates the transfer of power between power control areas. In addition, the power capacity of the specific power control area must be able to meet the power requirement as dictated by the load while coping with the power-sharing facilitated through AC tie lines keeping frequency and power interchanges at the scheduled values; and achieved by measuring a control error signal.

Solar PV generation is high on the South African power plan as an alternative energy source to supplement the growing energy deficiency. Solar PV is sustainable and environmentally friendly. The integration of PV power into electricity grids introduces system frequency problems due to the inherent intermittent nature of PV power generation systems. Despite the challenges presented by solar power generation and power system integration, solar power generation as an alternate power source is preferred due to the availability of solar radiation.

4.2 The concept of fuzzy controller

Classical controllers are unable to mitigate transient frequency deviation. Researchers have employed various design strategies to keep the system frequency and tie-line power within controlled limits. The literature on frequency stability approaches for thermal power plants and restricted for renewable energy technologies, i.e., solar power (PV). However, solar power is highly variable with respect to days and seasons, and that is why steam built power plants with PV power in interlinked mode will be a favourable choice for the researchers in the near future to meet the continuous power demand as well as to meet the frequency standards of South Africa.

Some researchers have used artificial intelligence (AI) tools, such as fuzzy logic (FL), to improve the limitations offered by conventional frequency controllers in order to address the frequency normalization problem. Robustness and reliability make the fuzzy controllers useful in solving a wide range of control problems. Several practical problems have fuzzy logic applied. This includes the control of warm water, robot, heat exchangers, power system, and nuclear reactors. A fuzzy logic system typically includes a fuzzifier, rule base, inference engines, and defuzzifier to produce the required output. The Fuzzy set hypothesis has been the protest of strongly consider and application, particularly within the final decade. Clearly, the presentation of fluffy control into ranges in which the investigation and plan of control frameworks is customarily performed utilizing procedures whose adequacy is well built up has driven to a certain separation within the way in which analysts and originators consider these unused strategies. In later writing, in reality, the suppositions communicated with respect to the value of these procedures habitually contrast. It ought to, in any case, be focused that the genuine issue does not lie in a coordinated comparison between 'new' and 'traditional' strategies but rather in their field of pertinence. In impact, within the field of displaying fluffy control were created to bargain with issues, which were difficult or incomprehensible to illuminate utilizing conventional methods.

Keeping in view, the above discussion, this chapter is dedicated to present the frequency control design for PV-Thermal model by designing various models of control oriented through fuzzy. The modelling of a solar PV generation scheme in a single order transfer-function domain is available in Chapter-3 of this report and reproduced as it is for further investigations and analysis. The studies have been performed utilizing the standard MATLAB program. The SIMULINK Tool kit is utilized to realize the outcomes and their examinations.

4.3 Application of Fuzzy Logic Techniques in Power System

The concept of fuzzy set hypothesis was presented in 1965 by Zadeh, and it was, to begin with presented in 1979 for tackling control framework issues. Fuzzy set hypothesis can be considered as a generalization of the classical set hypothesis. In classical set hypothesis, a component of the universe either has a place to or does not have a place to the set. Hence, the degree of affiliation of a component is fresh. In a fuzzy set hypothesis, the affiliation of a component can be persistently shifting. Scientifically, a fuzzy set could be a mapping (known as membership function) from the universe of talk to the closed interim {0, 1}.

The participation work is more often than not outlined by taking into thought the necessity and imperatives of the issue. FL actualizes human encounters and inclinations through enrolment capacities and fluffy rules. Due to the utilization of fuzzy factors, the framework can be made justifiable to a non-expert administrator. In this way, FL can be utilized as a common strategy to consolidate information, heuristics, or hypothesis into controllers and choice producers. Explanatory arrangement strategies exist for control framework issues. Be that as it may, the numerical details of control frameworks issues are determined beneath certain prohibitive suspicions, and indeed, with these presumptions, the arrangement of large-scale control framework issues isn't straightforward. On the other hand, there are numerous vulnerabilities in control framework issues since control frameworks are expansive, complex, topographically broadly dispersed, and impacted by startling occasions. These realities make it troublesome to viably bargain with numerous control frameworks issues through strict numerical details alone. Moreover, the customary controllers are fine for application in which the environment is known and unsurprising. But they can lead to the unacceptable when the suspicions upon which they are built are not followed. Not at all like the customary controller, the fuzzy controllers are versatile and alter to time or process-phase conditions and have the taking after points of interest:

1. Architects who utilize FL to create control frameworks are demonstrating productivity in their operation. By counting versatile control within the frameworks, they are able to plan frameworks that can alter to natural changes a basic calculate is standing applications. This versatile framework not as it were alters to time or process-phased conditions but moreover changes the supporting framework controls. This implies that a versatile framework adjusts the characteristics of the rules. Indeed a versatile FL framework is much more modern and includes a higher degree of versatile parameters.

2. FL endeavors to demonstrate computer thinking on the kind of imprecision and undesirability found in human thinking. Through fluffy rationale, a framework not as it were can speak to such uncertain concepts such as 'fast', 'tall', 'big' etc. But through a sound numerical guideline, it can to utilize these concepts to create conclusions around the frameworks.

3. Within the control field, a FL demonstrated to be exceptionally compelling in modeling complex, regularly non-linear frameworks. This modeling is as

a rule exceptionally fast, continues without a scientific demonstration and is based on an inexact representation of the control surface, and its behavior as the framework is bolstered with different input values. FLCs are less complex than ordinary controllers. They endure a certain imprecision in managing the issue of controls.

4.4 Fuzzy Logic Controllers

Unlike classical design approach, which requires a deep understanding of the system or exact mathematical models, FL incorporates an alternative approach. One of the most preferences behind the ubiquity of FLC is that it may be a model-free approach with tall capability of thinking beneath non-linearity and vulnerability. In any case, the plan process of fluffy controllers at a few point gets to be a trial-and-error strategy which needs an expansive number of redundancies, and thus it is time-devouring and repetitive. A FLC using error as input is equivalent to a proportional controller. If an error with integration is used as the input to the FLC, the controller behaves like an integral controller. When both error and rate of error are employed as inputs to the FLC the controller exhibits the characteristics of the proportional-integral controller. A FLC consists of three main processors, fuzzification, rule base and inference, and de-fuzzification as given in Figure 4.1.

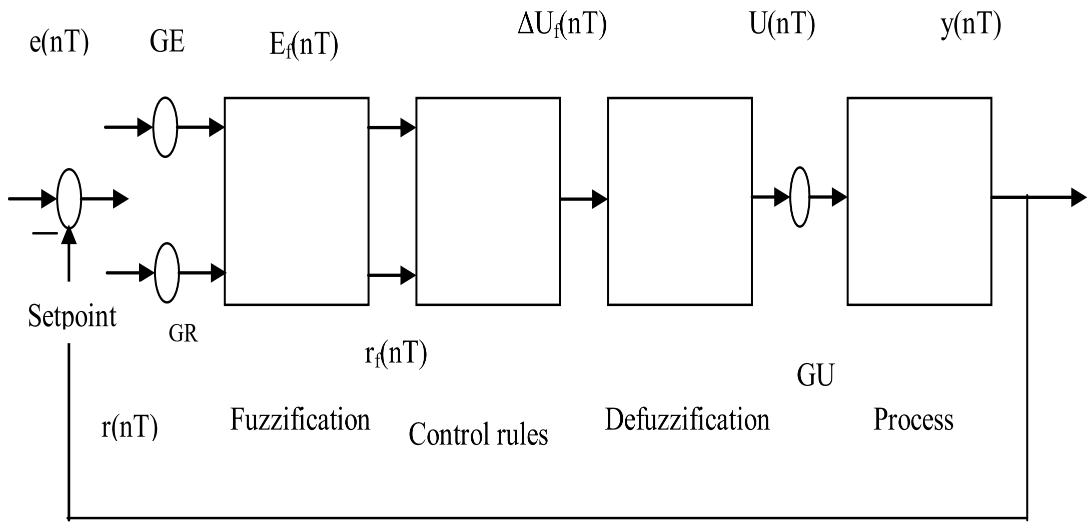

Figure 4.1: Block diagram representation for FLC

Fuzzification

Fuzzification is the method of changing crisp values to individual fuzzy factors concurring to the chosen membership capacities. The membership functions used for input and output variables are generally taken as triangular membership functions. According to the selected membership functions, each variable is assigned a number of linguistic values.

Rule Base and Inference

The Rule base of a FLC comprises of all the essential connections among the input and yield (control) factors. These connections are communicated within the form of in case---- and after---- that explanations. These are more often than not determined based on analytical, heuristically or master information around the framework behavior. Within the induction arrange, the rules are assessed to decide the values of fuzzy yield factors.

- **De-fuzzification**

De-fuzzification is the method of combining the outcomes about of inference system to discover crisp yields. A FLC can be represented by the block diagram in Fig. 4.1 Generally, the error ‘e’ and/or rate of change of error ‘r’ about a set point are employed as the input(s) to most of the FLCs.

$$e(nT) = y(nT) - setpoint \quad (4.1)$$

$$e_f(nT) = F[GE * e(nT)] \quad (4.2)$$

$$r(nT) = \frac{[e(nT - e(nT - T]}{T} \quad (4.3)$$

$$r_f(nT) = F[Gr * r(nT)] \quad (4.4)$$

$$\Delta U_f(nT) = F[GU * \Delta U(nT)] \quad (4.5)$$

$$U(nT) = \Delta U(nT) + U(nT - T) \tag{4.6}$$

Where, n is the positive integer T_s is a sampling period. The e(nT), r(nT), Y(nT), ΔU_f(nT) and U(nT) denote error, rate of change of error, process output; fuzzy output and crisp output from the fuzzy controllers G_E (gain for error) is the input scalar for error, Gr (gain for rate) is the input scalar for rate and GU (gain for controller output) is the output scalar of the fuzzy controller.[F] means fuzzification. The ΔU (nT) designates the incremental output of the Fuzzy controller (to process input) at sampling time nT. ΔU_f (nT) denotes the fuzzified value corresponding to ΔU (nT). e_f (nT) [r_f (nT)] denotes the fuzzy sets corresponding to scaled error GE*e(nT) [scaled rate GR *r(nT)].

4.5 Fuzzy Logic Design Built on Proportional-Integral (PI)

A nonlinear PI FLC can be developed by taking both 'area control error' and 'Integral of area control error' as the inputs. The 'area control error' and 'integral of area control error' are divided into five zones: negative Big, Negative Small, Zero Error, Positive Small, and Positive Big. The membership function is chosen as triangular and all symmetrical. The output of the controller is fuzzified into five zones Positive Big (PB), Positive Small (PS), Zero Error (ZE), Negative Small (NS), and Negative Big (NB). The design rules used for two-input PI FLC are given in Table-4.1, and for two sets of input, which are ACE and integration of ACE, the 25 possible sets of rules are formed to achieve the required action for interconnected PV-Thermal system. Further, the developed files of fuzzy inference system, input and output membership function, rule base, and surface viewer using MATLAB software are shown in Figure 4.2-4.7.

		ACE				
		NB	***NS***	***ZE***	***PS***	***PB***
∫(ACE) dt	***NB***	NB	NB	NS	NS	ZE
	NB	NB	NB	NS	NS	ZE
	NS	NB	NS	NS	ZE	PS

	ZE	NS	NS	ZE	PS	PS
	PS	NS	ZE	PS	PB	PB
	PB	ZE	PS	PB	PB	PB

Table 4.1 Rule base for Fuzzy PI for PV-Thermal System

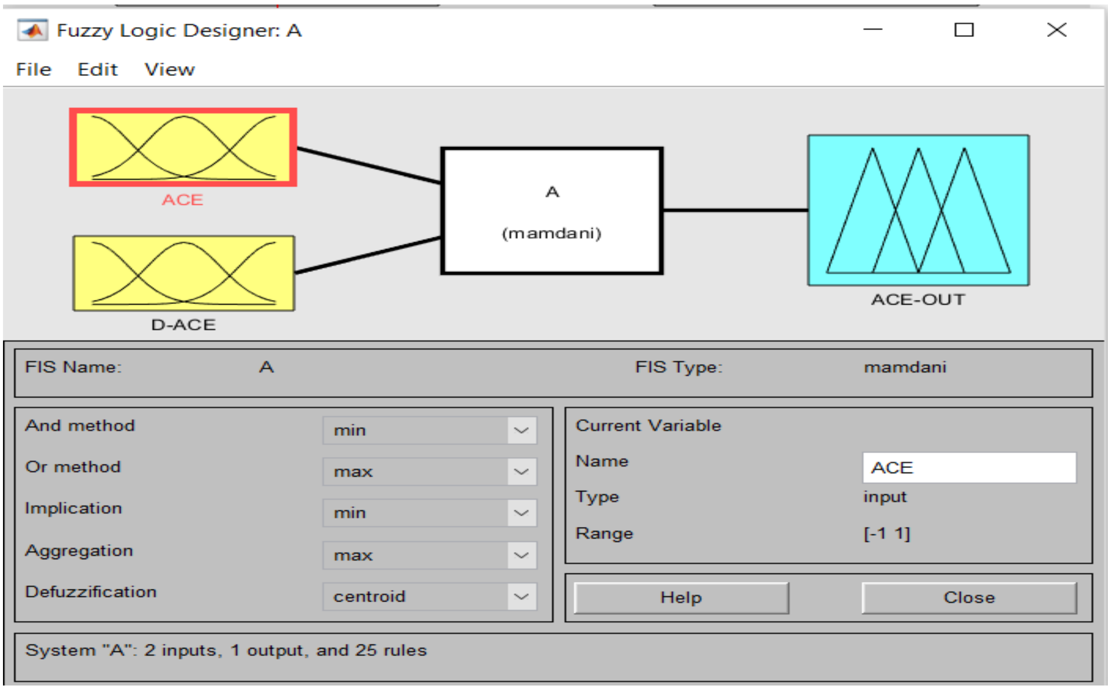

Figure 4.2: Developed fuzzy inference system for Fuzzy PI using MATLAB

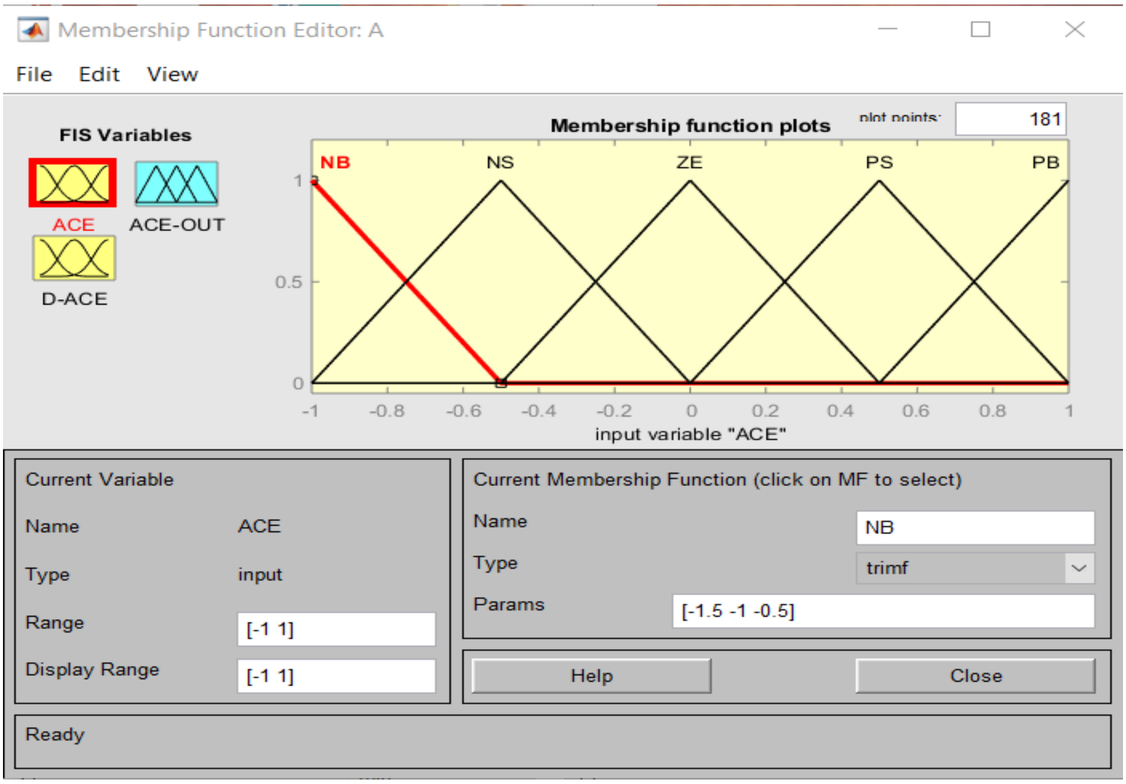

Figure 4.3: Input membership function of Fuzzy PI developed using MATLAB

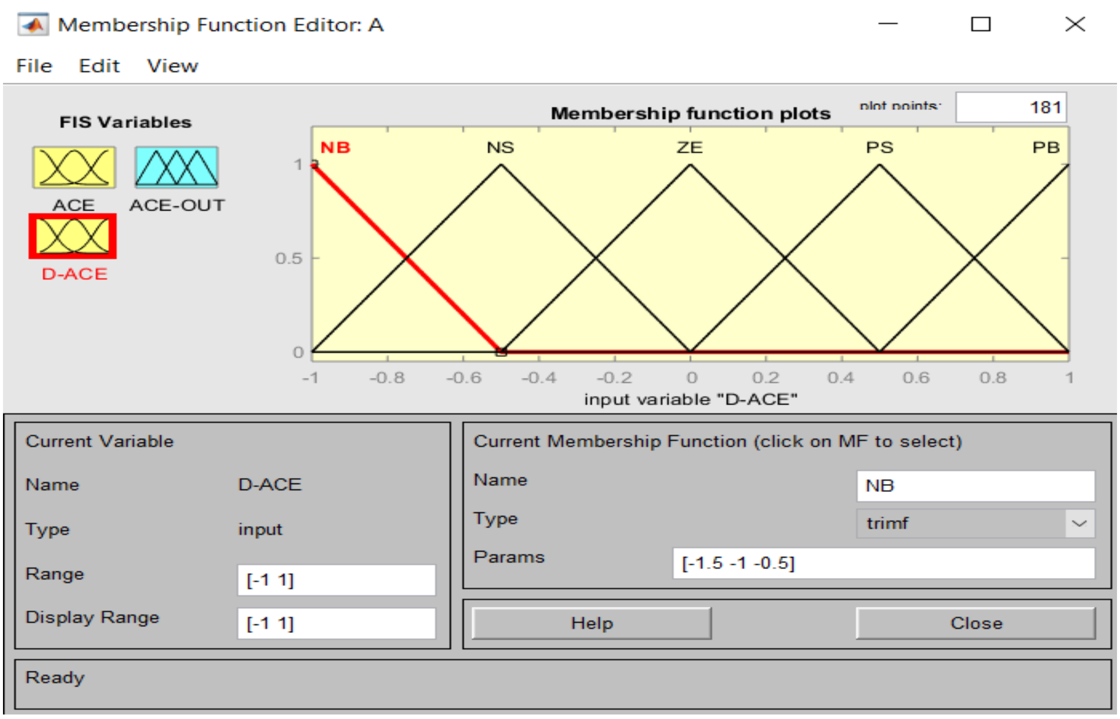

Figure 4.4: Input membership function of D-ACE of Fuzzy PI using MATLAB

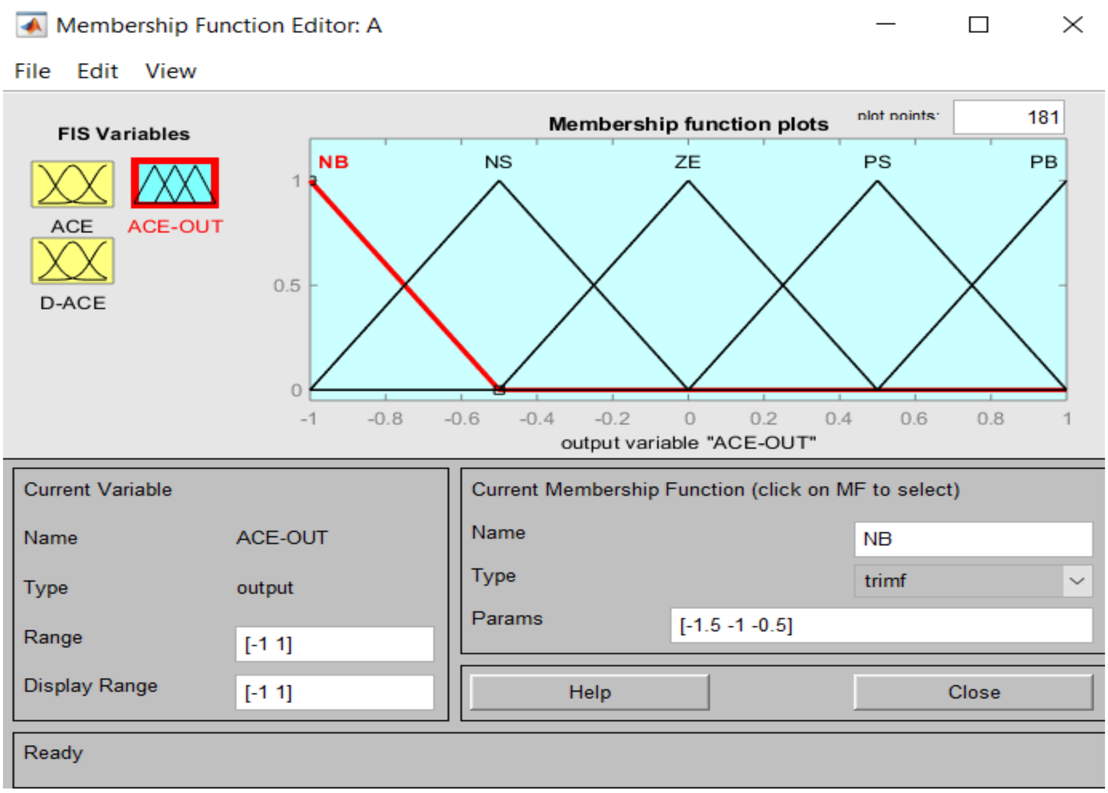

Figure 4.5: Output membership function of Fuzzy PI using MATLAB

Figure 4.6: Rule base of Fuzzy PI developed using MATLAB

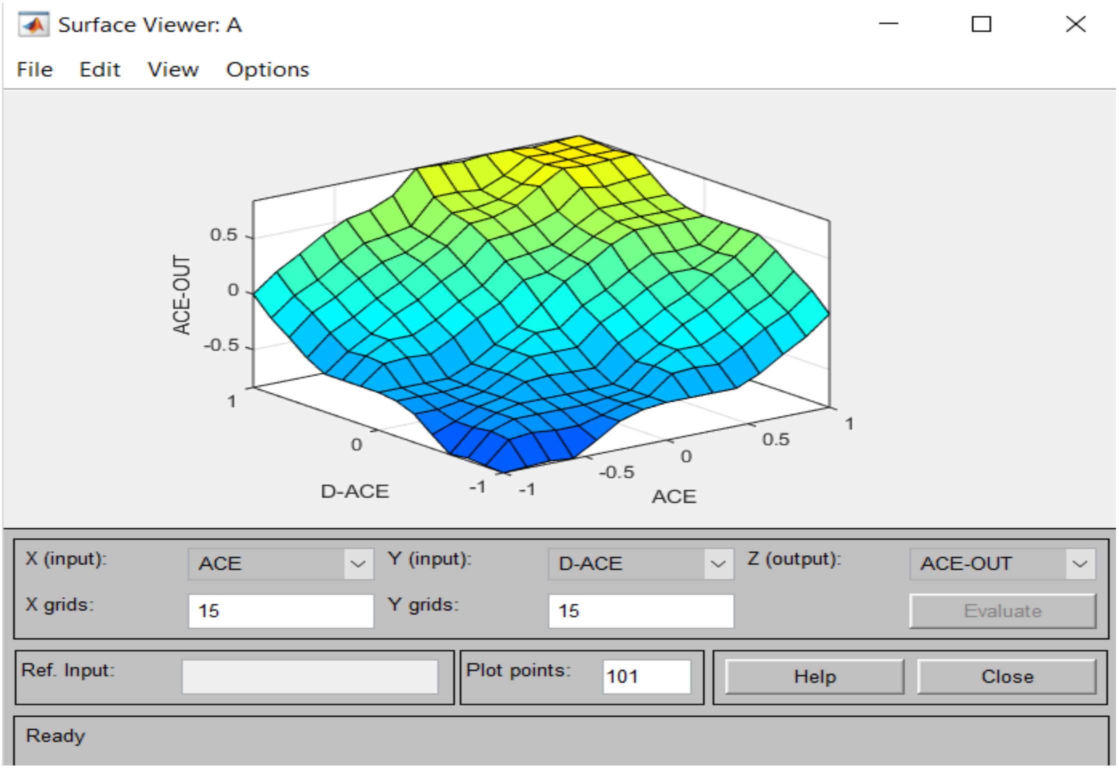

Figure 4.7: Three dimensional surface viewer of Fuzzy PI using MATLAB

4.6 FL design built on proportional Control

Proportional control action using FL can be obtained by taking into consideration only ‘area control error (ACE)’ at every sampling instant of the controller. Further, the developed files of fuzzy inference system, input and output membership function, rule base, and surface viewer using MATLAB software for proportional FLC are shown in Figure 4.8 - 4.11. The area control error and incremental output of the controller are fuzzified into five zones in order to achieve proportional FL action. Following rules as listed in Table 4.2 is used for obtaining the characteristics of a proportional FLC;

Table 4.2 Rule base for Proportional FLC

R1	IF AĈE is PB THEN, ΔPc is PB
R2	IF AĈE is PS THEN, ΔPc is PS
R3	IF AĈE is ZE THEN, ΔPc is ZE

R4	IF AĈE is NS THEN, ΔPc is NS
R5	IF AĈE is NB THEN ΔPc is NB

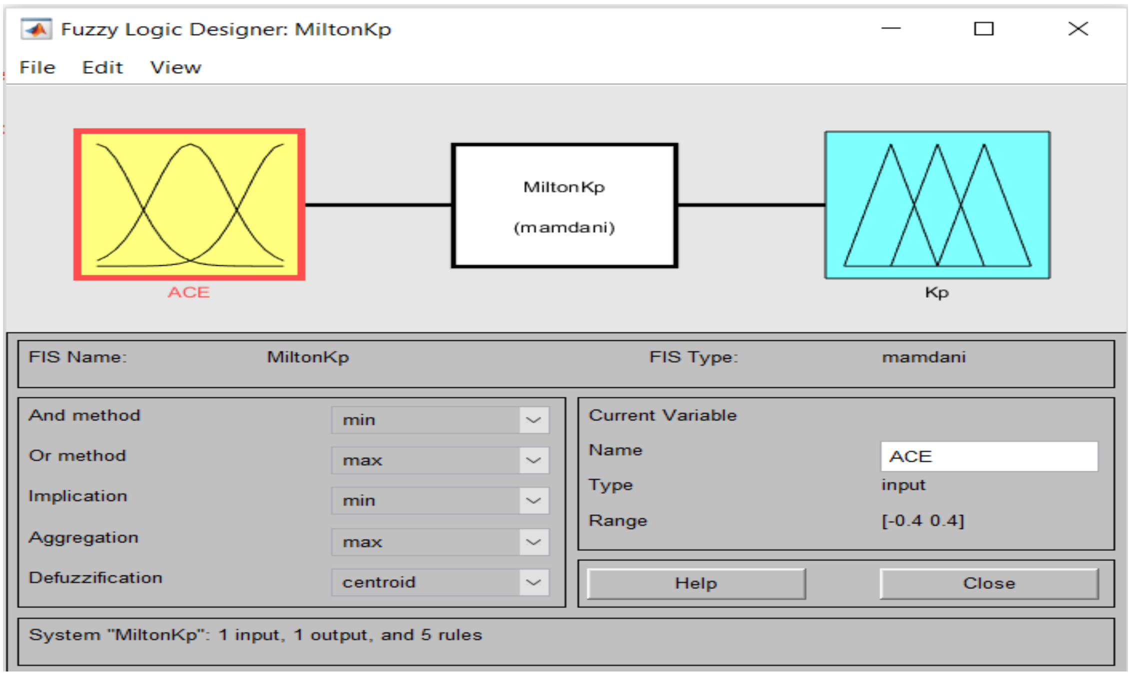

Figure 4.8: Fuzzy inference system for proportional FLC using MATLAB

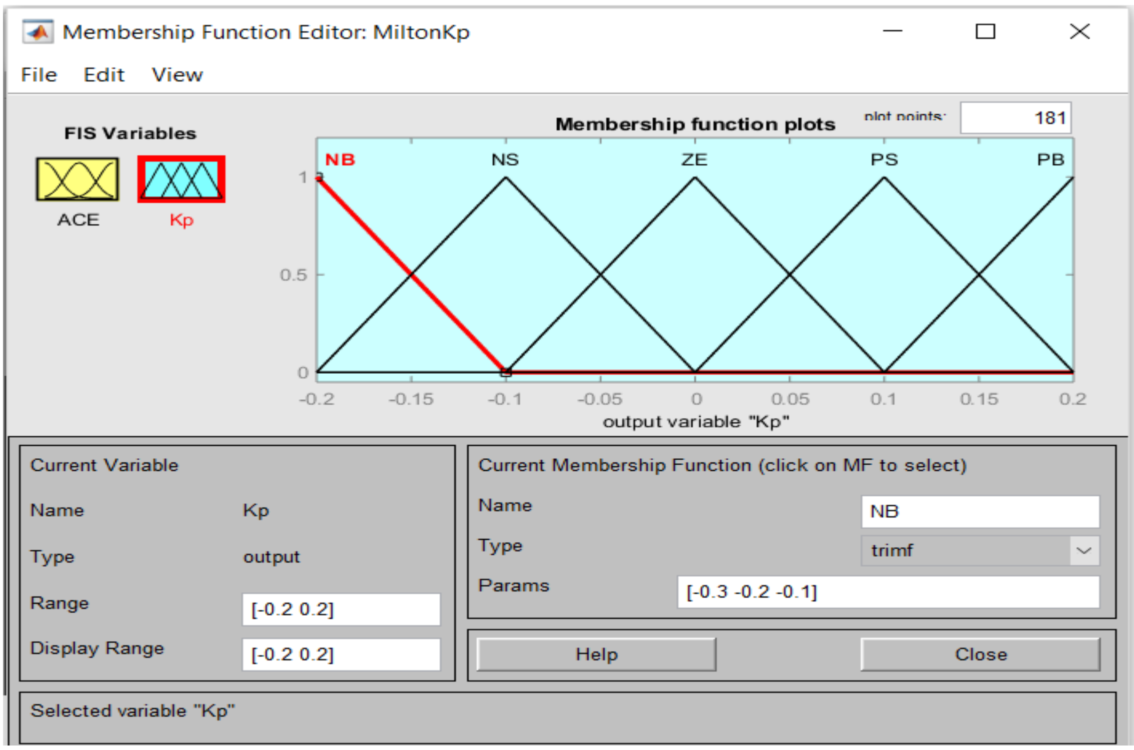

Figure 4.9: Output membership function for proportional FLC using MATLAB

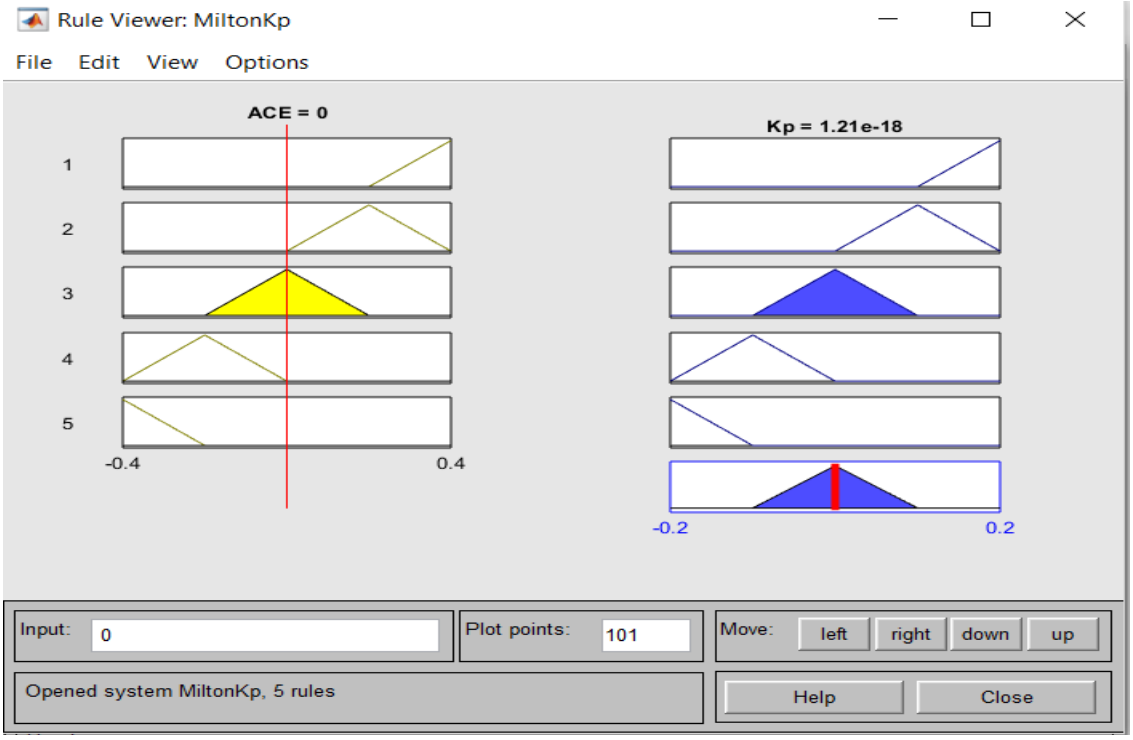

Figure 4.10: Rule base of proportional FLC using MATLAB

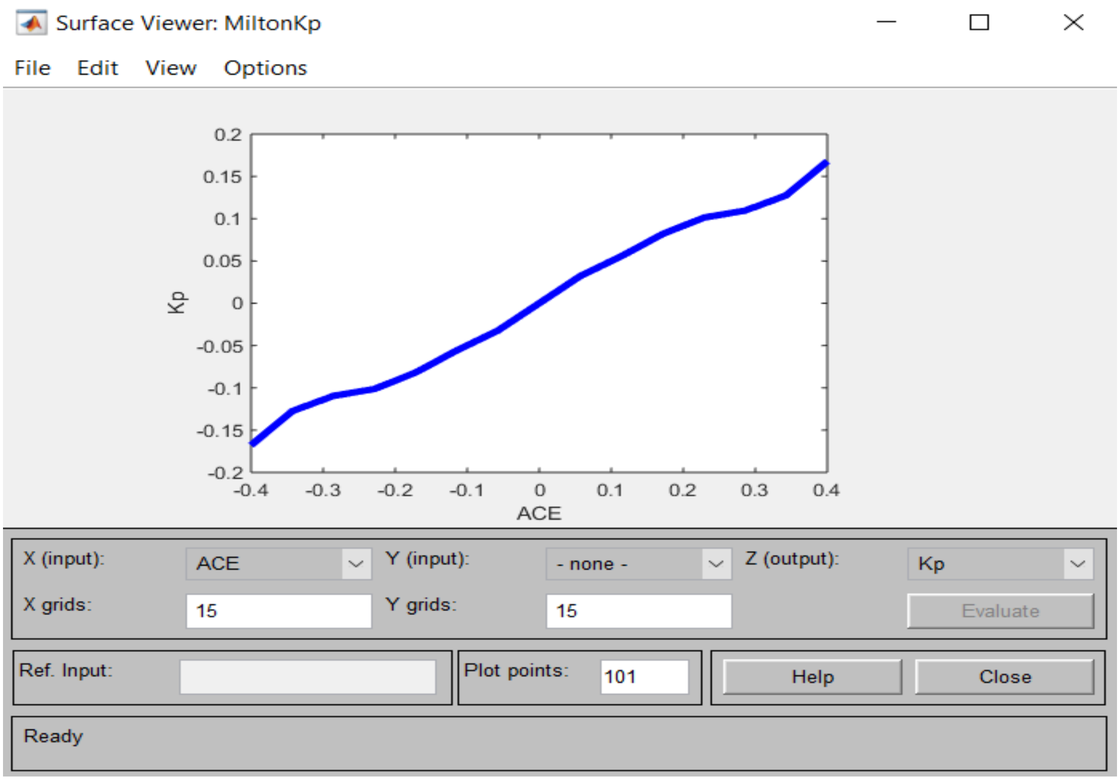

Figure 4.11: surface viewer of proportional FLC using MATLAB

4.7 FL design built on integral FLC

Integral control action using FL can be obtained by taking into consideration the integral of area control error at every sampling instant. The area control error is the input to the FLC, and the output of the controller is the crisp value of the incremental output after fuzzification. Then, the real change in output is obtained after the defuzzification of the values. Following rules as found in Table 4.3 is used to get the integral control action;

Table 4.3 Rule base for Integral FLC

R1	IF ACE is NB THEN, ΔPc is PB
R2	IF ACE is NM THEN, ΔPc is PM
R3	IF ACE is NS THEN, ΔPc is PS
R4	IF ACE is PS THEN, ΔPc is NS
R5	IF ACE is PM THEN, ΔPc is NM
R6	IF ACE is PB THEN, ΔPc is NB

The developed files of fuzzy inference system, input and output membership function, rule base and surface viewer of integral FLC using MATLAB software are shown in Figure 4.12-4.16

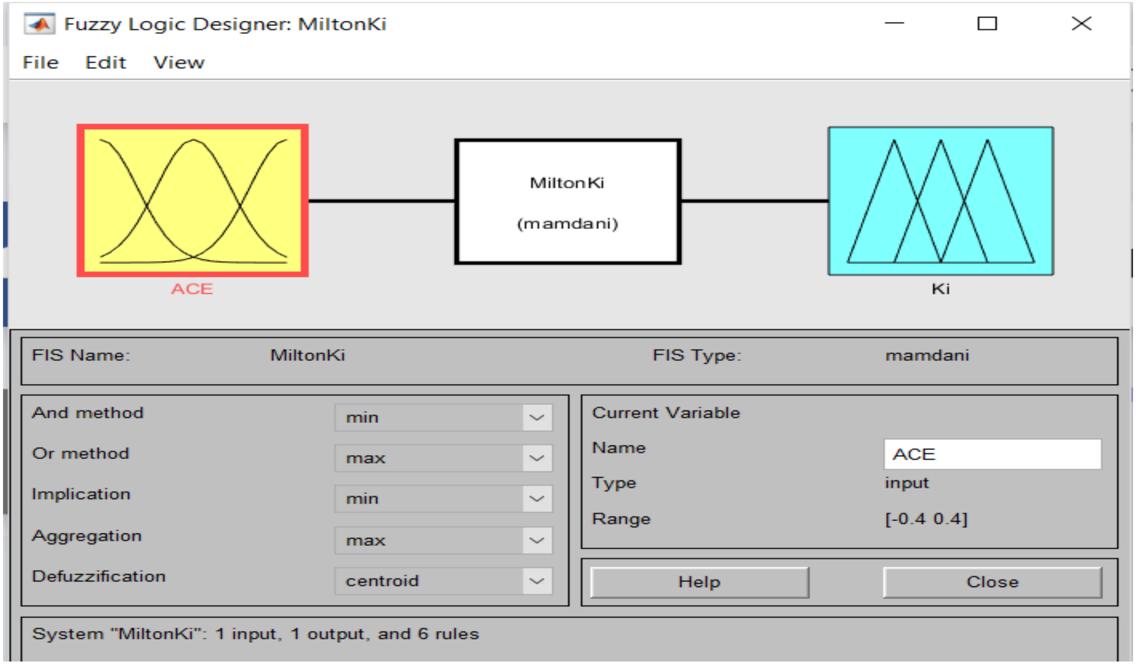

Figure 4.12: Fuzzy inference system of integral FLC using MATLAB

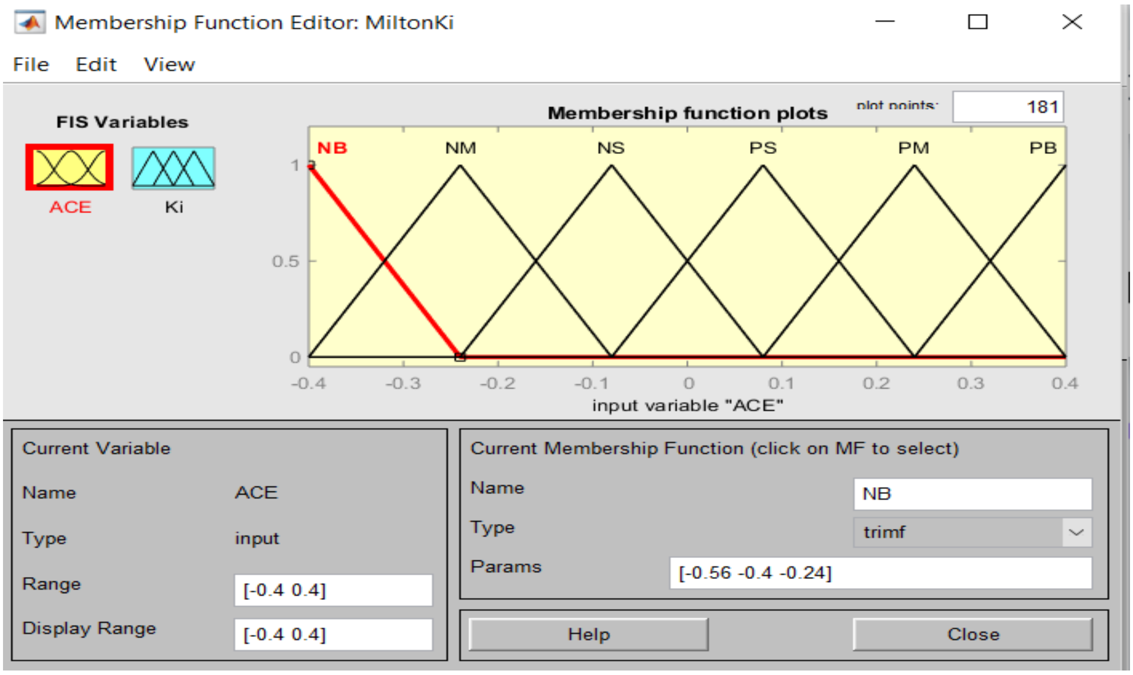

Figure 4.13: Input membership function of integral FLC using MATLAB

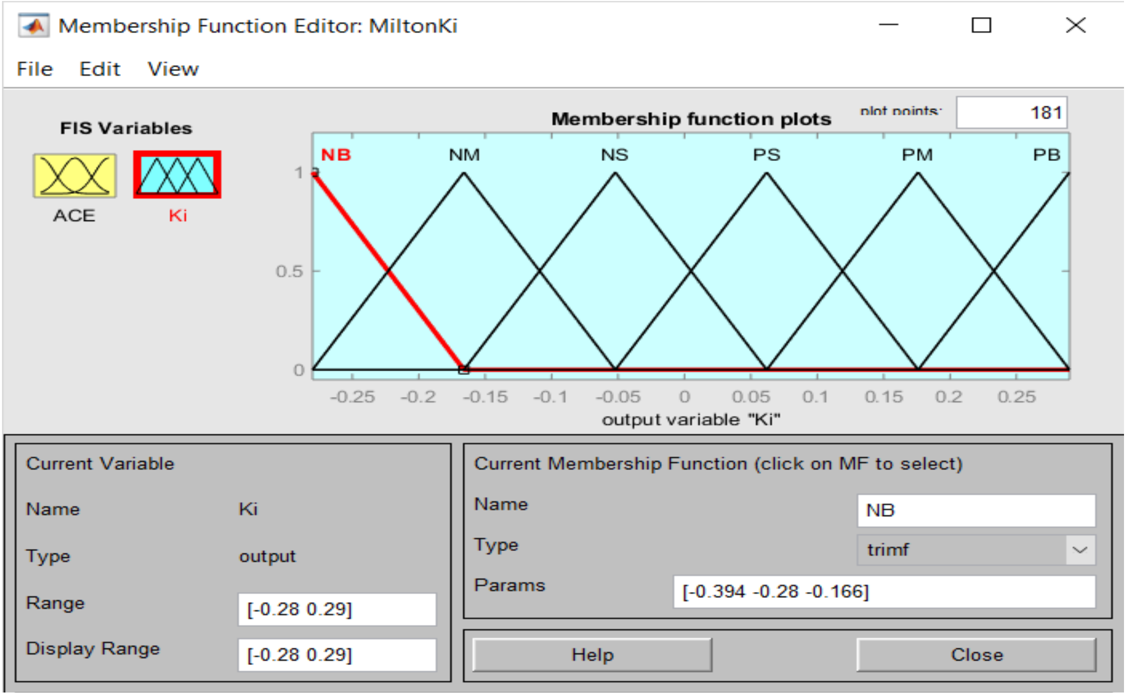

Figure 4.14: Output membership function of integral FLC using MATLAB

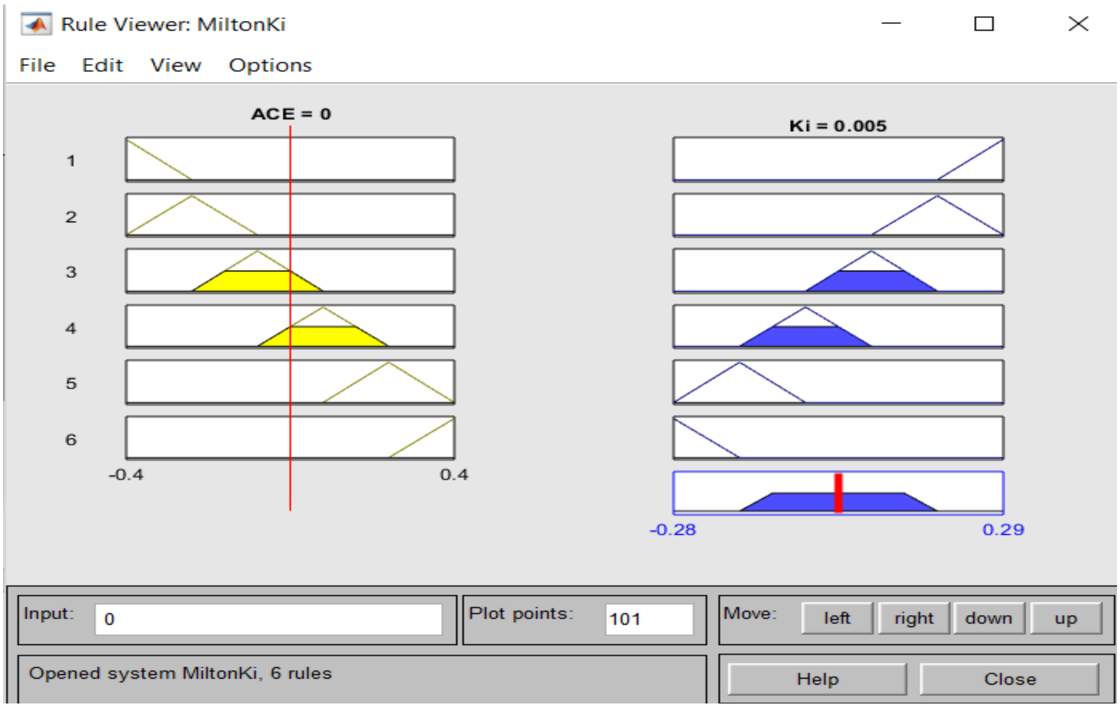

Figure 4.15: Rule viewer of integral FLC using MATLAB

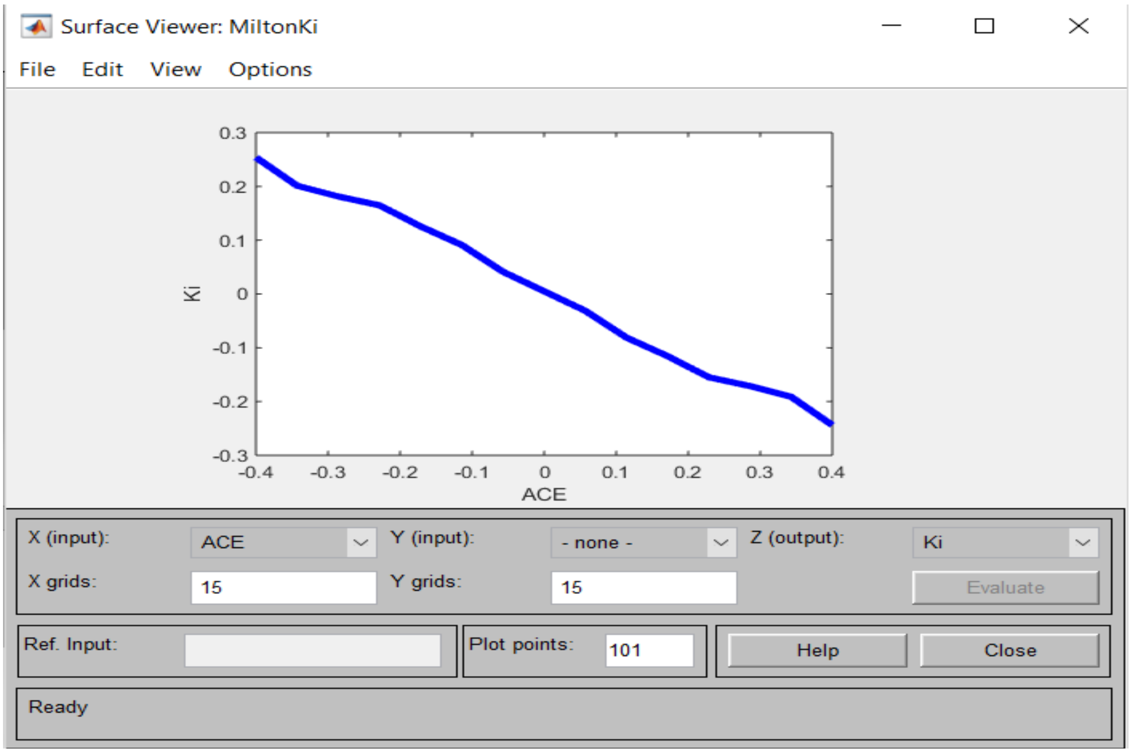

Figure 4.16: Surface Viewer of Fuzzy Integral Controller

4.8 Summary of the Chapter

This chapter presents the need and design of fuzzy logic controllers for linked PV-thermal systems. The various modes of fuzzy logic, i.e., proportional-integral, proportional, and integral control using fuzzy logic, were designed using standard MATLAB software. The impact of these control actions in achieving the frequency standard of PV-Thermal is checked, and the results are shown and scrutinize in the next chapter of this report.

CHAPTER FIVE

Results & Analysis

This chapter considers the simulation results and analysis of chapter-3 and chapter-4, respectively. The results were simulated using MATLAB Simulink software.

5.1 Simulation results of PID controller

The results displayed here are from the various modes of PID controllers as designed in chapter-3. The controllers compared are proportional integral (PI), proportional derivative (PD), Classic PID, Pessen intergral rule, some overshoot, and no overshoot modes. The interconnected network is designed to study the frequency and tie-power variations with respect to variable load demand in thermal or PV power control areas. The two control areas are linked via means of AC tie-line. The diverse modes of PI, PD & PID design for each control areas in order to bring back the frequency and tie-line power fluctuations back to the desired value in the minimum possible time (seconds). The goal of secondary controllers is to achieve the frequency stability for certain load variation with minimum overshoot, least settling time & acceptable steady-state error for frequency, tie-power variations & ACEs. The Zeigler-Nichols tuning technique is adopted to improve the system responses. At first, the ultimate gain (Ku) and ultimate time period (Tu) is evaluated via having the load disturbance in thermal area, and the value of ultimate gain and ultimate time is noted for frequency stability studies for each control area. Finally, the gains of various modes of controllers are evaluated with the help of Table 3.1 as discussed in chapter-3. The calculated gains for PI, PD, classic PID, Pessen integral rule, Some overshoot, and No overshoot are given in Table 3.2 for PV and for thermal power in Table 3.3 of chapter 3. The performance of interconnected solar thermal is evaluated on obtained gains as given in Table 3.2 & Table 3.3 for various methods for step load disturbance in thermal area, and the comparative results for frequency, tie-power variation as well as ACEs of both areas are shown in

Figure 5.1-Figure 5.5. The results displayed in figure 5.1 were taken from the PV area of the interconnected system indicated as Δf_1.

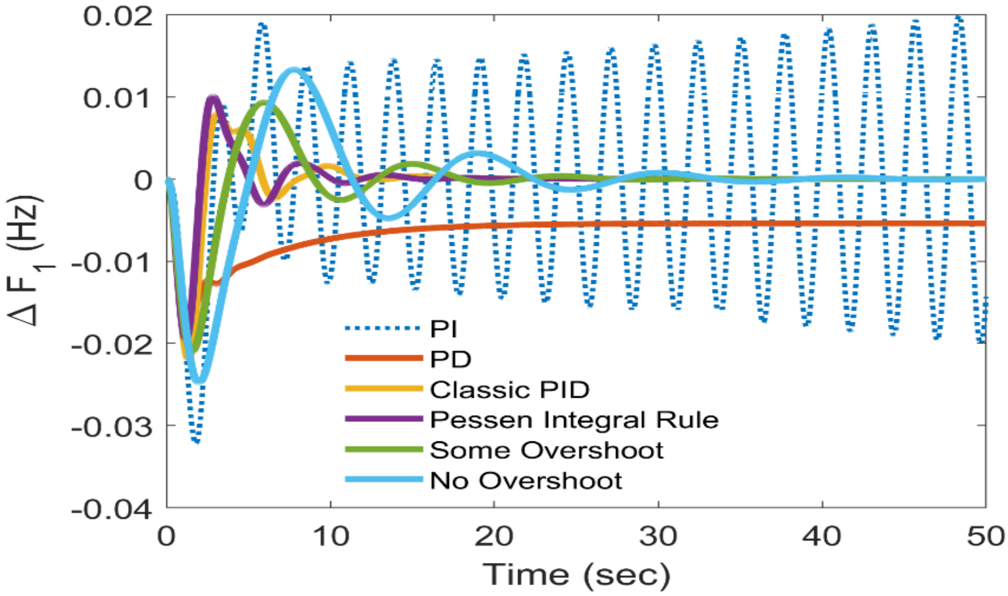

Figure 5.1. System results for step load disturbance in area-1

The results displayed in figure 5.2 were taken from the THERMAL area of the interconnected system indicated as Δf_2

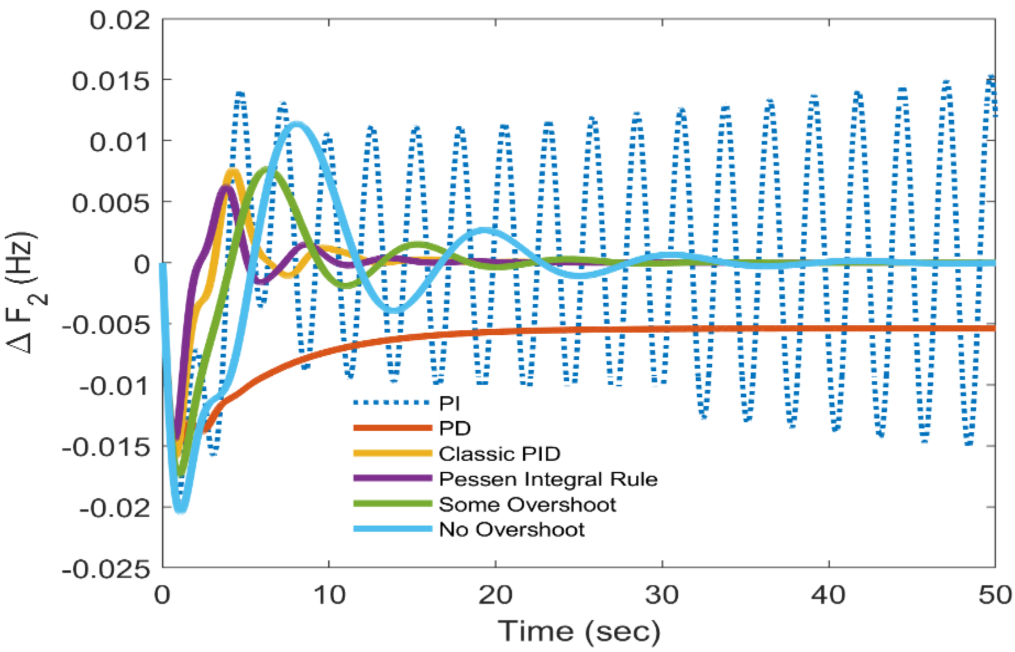

Figure 5.2. System results for step load disturbance in area-2

The results displayed in figure 5.3 were taken from the Tie-line of the interconnected system indicated as ΔP_{tie12}.

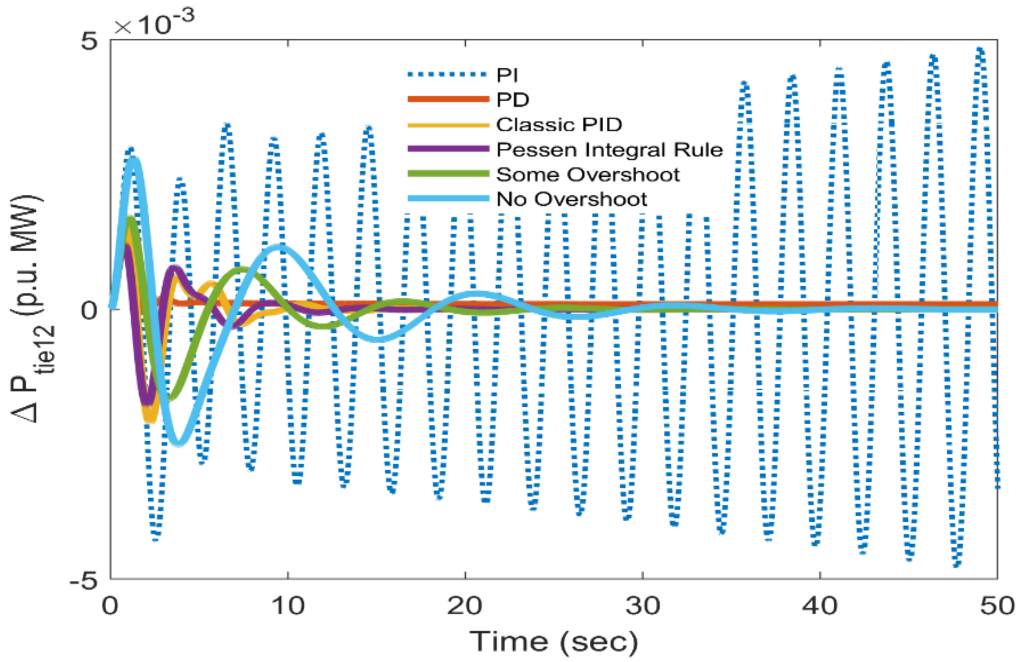

Figure 5.3. System results for step load disturbance in area-2

The results displayed in figure 5.4 were taken from the PV area of the interconnected system indicated as ACE_i

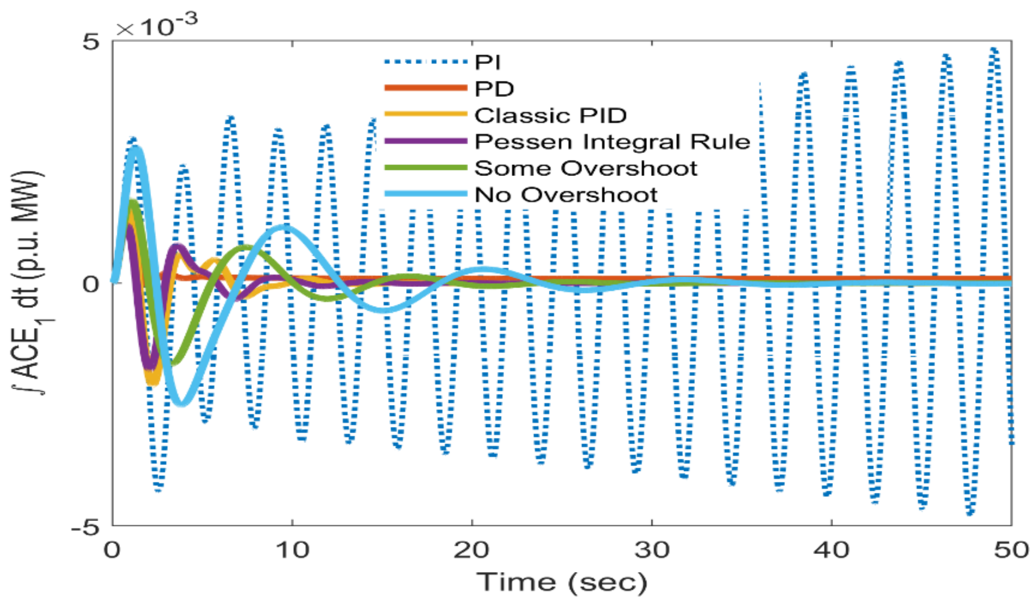

Figure 5.4. System results for step load disturbance in area-1

The results displayed in figure 5.5 were taken from the THERMAL area of the interconnected system indicated as ACE_2

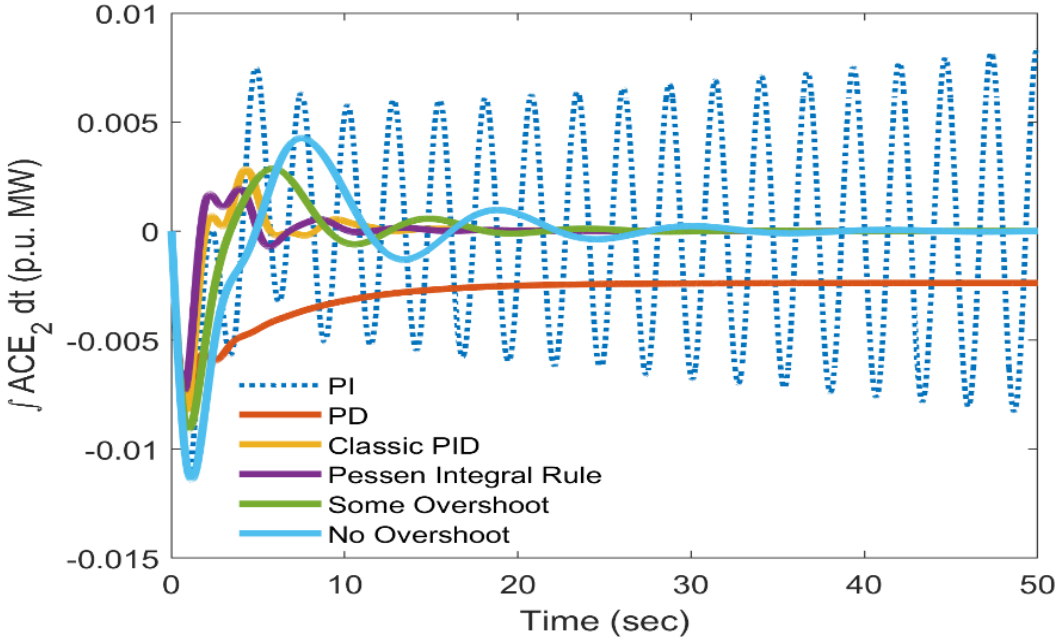

Figure 5.5. System results for step load disturbance in area-2 (e)

5.2 Analysis of results for PID controller

A look at these results clearly shows that error exist in responses of PD and it is not acceptable for the considered system. The outcomes acquire via PI have the sustained oscillations for frequency, tie-line power & ACEs of both areas which are also not desirable considering the quality power delivered by the system. The results offered by No overshoot method are better than PI & PD but still having oscillations as well as settling time is 30 seconds for all responses. The results of Classic PID and some overshoot are better for all responses in terms of reduction in first peak of overshoot with lesser settling time in comparison to that obtained via PI, PD & No overshoot method. However, the best system responses are obtain by Pessen integral rule with (-0.02) Hz of frequency variation in PV area with settling time of 13 seconds and zero steady-state error. The same is also observed for thermal area with maximum peak of (-0.015) Hz with settling time of 10 seconds & zero error between the desired and actual value. The same effect observe in tie-line power variation as well as ACEs of both areas and hence it is observe that Pessen integral rule provides promising performance in suppressing the frequency, tie-line power, and ACEs variations back to the original value in minimum possible time. From the results, it is also observed that the first peak of overshoot is high in frequency variation of PV area (-0.02 Hz) in comparison to thermal area (-0.015 Hz) for Pessen integral rule under the same functional settings. The settling time is also less for thermal power in comparison to PV. The system responses may get worse in case a disturbance is applied in PV control area, as in present case all results are captured by having step disturbance in thermal power area. This is due to fact that thermal power plants are more stable & rigid power plants in comparison to PV power for variable loading conditions. However, the obtained results are within acceptable limits.

5.3 Simulation results for fuzzy controllers

The results displayed here are from the fuzzy logic controllers designed in chapter 4. The controllers compared are proportional fuzzy logic, intergral fuzzy logic, and proportional intergral fuzzy logic. The present investigation is to deliberate the possible examination of power generation and grid integration of PV to well establish plants having thermal power generation framework coming into an interconnected system and playing a dynamic part in managing the balance between generation and load cost-effectively. The connectivity is a plan to take into account the variable load frequency and tie-power deviation in PV control or thermal control regions. The two control areas, one with PV and another with the thermal founded generation, are connected through implies of AC tie-line.

The different modes of proportional, integral, and proportional-integral control are initiated in respective zones in the arrangement. This restores the tie-line deviation and frequency control variances to the original magnitude under a conceivable period (second). The objective of auxiliary control is to realize the frequency, tie-power deviations, and ACEs of each control zones with least overshoot, slightest settling time & satisfactory system responses for each control zones. Earlier, the control efforts were design on the basis of conventional control way in order to achieve the standards of the system. However, conventional approaches are time-consuming and entirely unacceptable for different operating conditions. Hence, the concept of FL is used to design the control efforts for the linked PV-Thermal system. These are proportional FL, Integral FL, and FL action put in place to achieve the complete efforts and known as FL built PI for linked PV-Thermal System. In order to achieve the proportional FLC, the error, which is ACE of different control zones are input to the FL action. Hence for proper fuzzification and to obtain a proportional response from FL, the input is divided into five zones, which are PB, PS, ZE, NS, NB; the output is also divided into five zones considering triangular membership function. The design set of rule base is given in Chapter-4 to achieve the proportional action from FL. After this, the ACE is integrated and input to FL.

To obtain FL base integral action, the ACE is divided into six zones, which are NB, NM, NS, PS, PM, PB, and the output of FL is also divided into six zones with triangular membership function chosen for FL. This is due to simplicity and symmetry. The complete set of rule bases for integral FLC is given in chapter-4 of this report. Finally, to obtain the complete efforts for the linked PV-Thermal system, the error and differentiation of error, which is ACE and D-ACE is used as input to PI built FL. The input ACE and D- ACE are divided into NB, NS, ZE, PS, and PB, and the output of FL is also divided into five zones with triangular membership function for inputs and output of PI built FL. For two inputs and one output from FL, the total 25 possible combinations are possible, and that is why PI built FL has a set of 25 rules for linked PV-Thermal system.

The complete rule base is given in chapter-4. The output is defuzzified through the centroid method in order to convert the crisp value to real values and input to the PV as well as thermal power to change the generation as per change in load demand. Finally, the performance of all design FL is tested on a linked PV-Thermal system for a 2% load change in the thermal control zone. The comparative analysis of all FL is carried out with respect to responses for frequency, tie-power, and ACE alteration. These responses, which are obtained via all FL, are shown in Figures 5.6-5.10. The results displayed in figure 5.6 were taken from the PV area of the interconnected system indicated as Δf_1. The results displayed in figure 5.7 were taken from the THERMAL area of the interconnected system indicated as Δf_2. The results displayed in figure 5.8 were taken from the Tie-line of the interconnected system indicated as $\Delta P_{tie12.}$ The results displayed in figure 5.9 were taken from the PV area of the interconnected system indicated as ACE_i. The results displayed in figure 5.10 were taken from the THERMAL area of the interconnected system indicated as ACE_2.

The results show that proportional FL action has a lower overshoot for tie-power alteration, frequency, and ACEs of the two control zones for load change in the thermal control zone, and also, the output is free from oscillations entirely. However, still, the error exists between the required and actual output of the system from proportional FL based action. On the other side, the response of integral FL has sustained oscillations, and oscillations exist in responses for 50 seconds also for PV as well as for thermal control zones and for other responses also. The overshoot of integral FL is also higher with regards to proportional FL. However, due to integral control efforts obtain via FL the all system responses reach back to steady-state value quickly. With regards to proportional FL and integral FL, the responses of tie-power, frequency, and ACE alteration of the two areas are much better in all aspects of system output obtain via PI built FL.

The overshoot is very less with regards to other FL actions as well as the responses of all outputs are free from oscillations. Further, all system responses reach back to their original values within 10 seconds only, which is highly required in frequency normalization of linked PV-thermal system. Thus it clearly shows that out of all FL action, the fuzzy PI can quickly set the balance between generation and load alteration and hence to limit the frequency normalization in the best possible time. From the results, it is observed that the overshoot crest is more for the frequency alteration of the PV zone (-0.06 Hz) when co-ordinated to the frequency dip (-0.04 Hz) for thermal control zone, despite the load alteration in the thermal control zone of linked PV-thermal system. The settling time is additionally lower in thermal control when compared to PV.

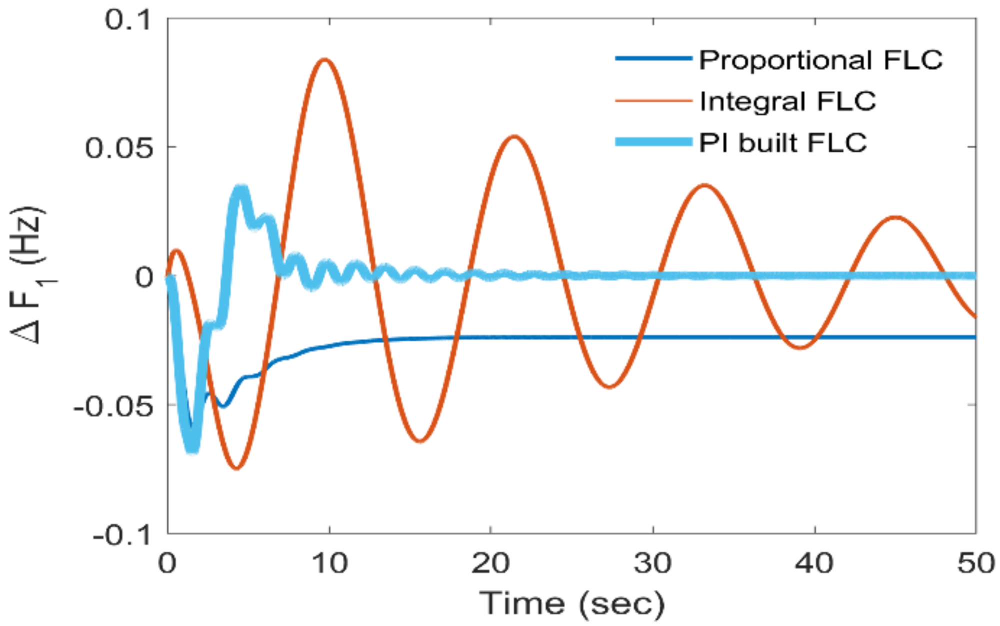

Figure 5.6. System results for step load disturbance in area-1

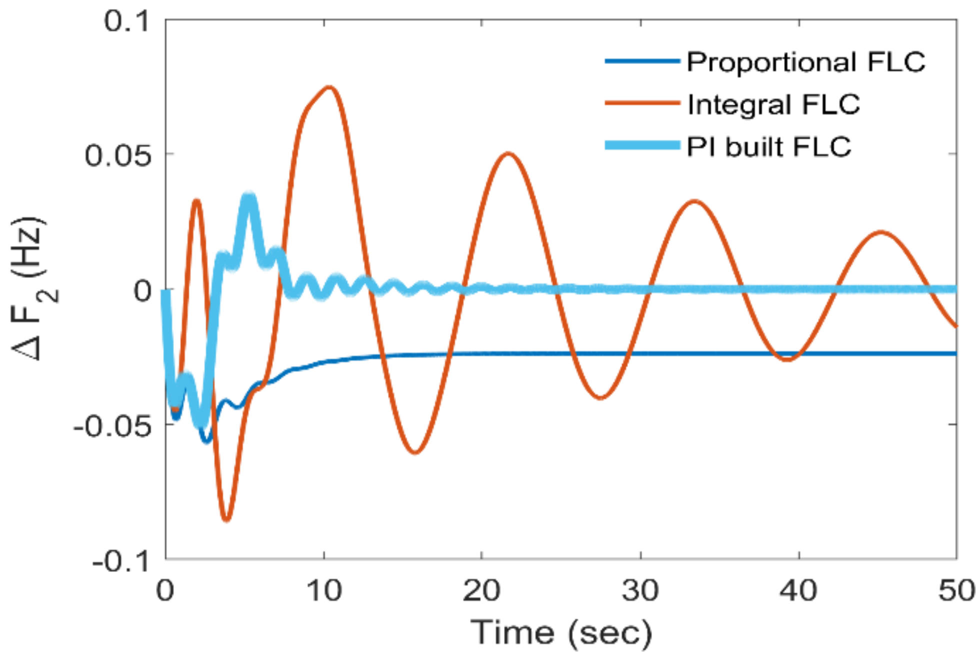

Figure 5.7. System results for step load disturbance in area-2

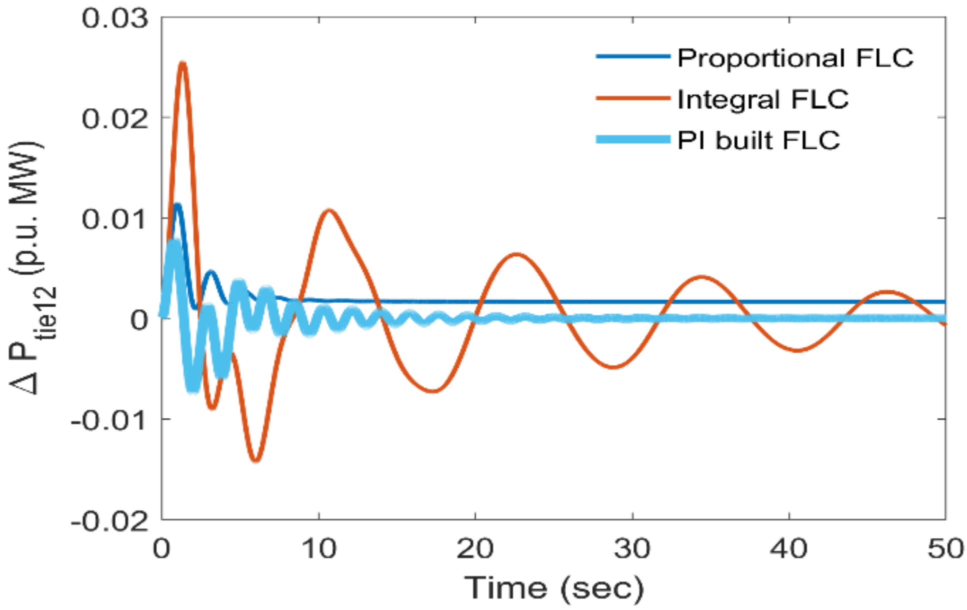

Figure 5.8. System results for step load disturbance in area-2

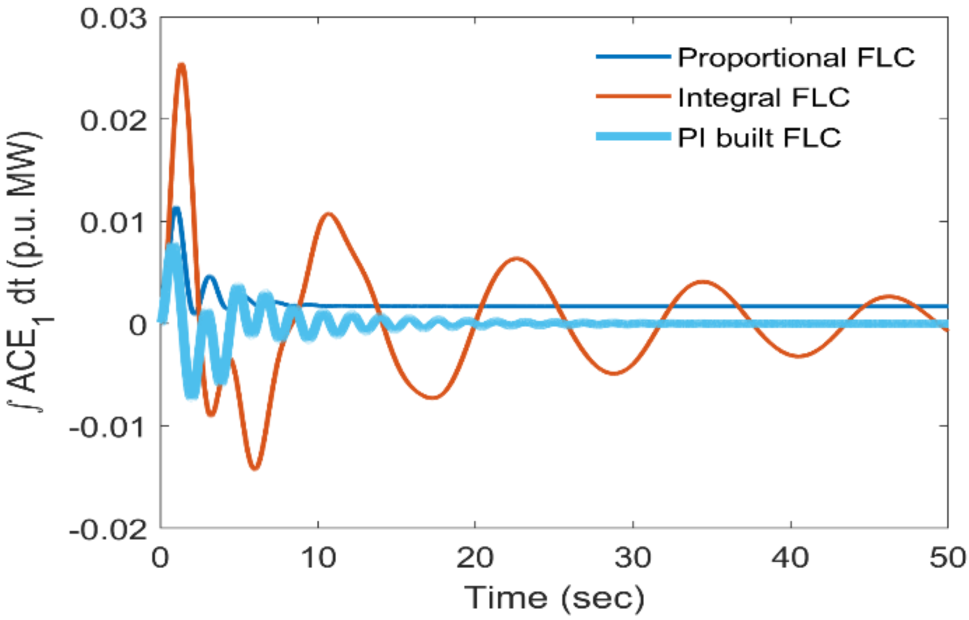

Figure 5.9. System results for step load disturbance in area-1

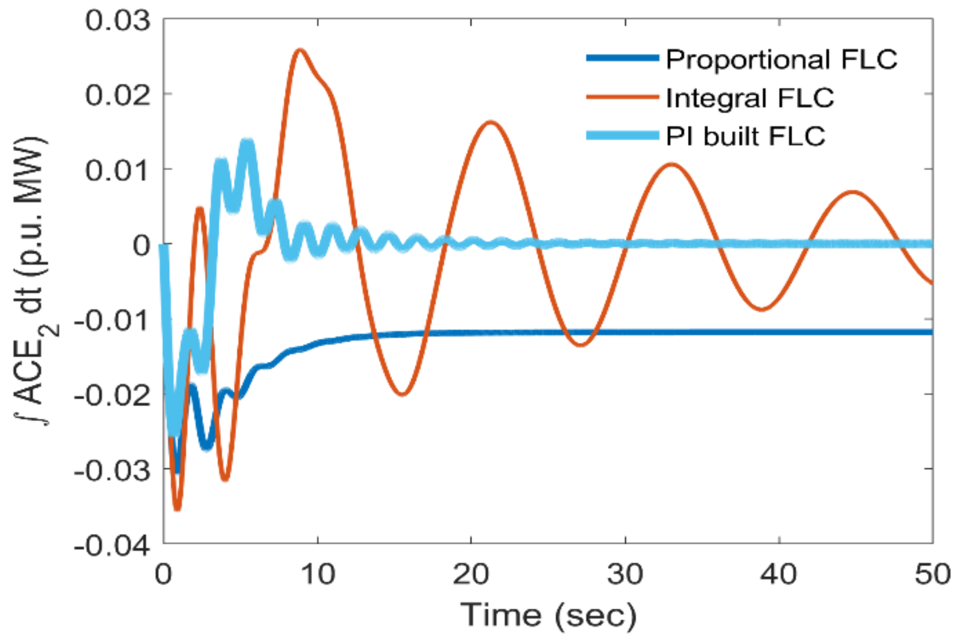

Figure 5.10. System results for step load disturbance in area-2

5.4 Summary of the Chapter

This chapter shows the results analysis of PID and fuzzy oriented action for frequency managing of PV-Thermal system. It is observed that Fuzzy PI is managing better system frequency conditions when matched with others for PV-Thermal. It is also seen that the peak of waves is high in PV in comparison to thermal as thermal are stable models and able to manage the generation quicker than PV for any unpredictable load demand. The complete conclusions of the work with future possible research direction are shown in the next chapter of the report.

CHAPTER SIX

Conclusions and Recommendations

6.1 Conclusions

The aim of this study is to design and model PID controllers and fuzzy oriented using various modes to mitigate frequency fluctuations in the interconnected system and to evaluate which controller gives the best results. The aims and objectives as outlined in chapter one of this thesis were achieved.

The inter-connected PV-thermal model were used to test the various classical PID modes as well as the various fuzzy logic modes. MATLAB Simulink software was used to simulate all results.

In the case of various PID controllers such as PD, PI, classic PID, Pessen integral rule, some overshoot and no overshoot, the results reveal that the Pessen integral rule controller was the most superior for frequency managing of PV-Thermal when coordinated with other designs.

The Pessen integral rule established PID controller restored the system back to its original value in minimum time with reduced first peak and good damping, which is not possible by other PIDs.

In the case of fuzzy controllers, the different modes of proportional, integral and proportional-integral control built on fuzzy logic were initiated for each control area for frequency normalization studies.

The results reveal that the fuzzy PI controller is more favourable in terms of restoring nominal system frequency value in minimum time and in addition offered greater dampening and reduced overshoot when coordinated with other fuzzy actions. This study further revealed that the frequency of PV system is highly disturbed in comparison to thermal plant as they are interlinked via AC tie-line.

6.2 Future Research Areas

In the present, study the aim is to develop the good control action for PV-Thermal linked energy systems to bring back the frequency and tie-power within its limits after certain load change. However, still there is a scope of improvement and direction for further research, which are as follows:

1. The present work is limited to step load disturbance. However, in reality, load changes continuously and that is why it is important to design an action, which will manage the system continuously and act continuously i.e., action built on load forecasting technique.
2. The work can be extended to system non-linearity, parametric alterations, and random load disturbances.
3. The present model was developed in view of the regulated environment, and as South Africa is moving towards energy competition and quality and hence this work can be extended to deregulate market scenario in view of various market transactions.
4. Further, the problem of FL can combine with optimization techniques to design a more robust control design for PV-Thermal systems.

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