

**A FUZZY BASED LOAD FREQUENCY CONTROL AND LOAD
SHEDDING SCHEME FOR ISLANDED DISTRIBUTION
NETWORK CONNECTED WITH MINI-HYDRO**

JAVED AHMED LAGHARI

**DISSERTATION SUBMITTED IN FULFILMENT OF THE
REQUIREMENT FOR THE DEGREE OF MASTER OF
ENGINEERING SCIENCE**

**FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR**

2012

UNIVERSITI MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: **JAVED AHMED LAGHARI** (I.C/Passport No:

Registration/Matric No: **KGA 100025**

Name of Degree: **MASTER OF ENGINEERING SCIENCE**

Title of Project Paper/Research Report/Dissertation/Thesis (“this Work”):

**A FUZZY BASED LOAD FREQUENCY CONTROL AND LOAD SHEDDING
SCHEME FOR ISLANDED DISTRIBUTION NETWORK CONNECTED WITH
MINI-HYDRO**

Field of Study: **ELECTRIC POWER SYSTEM**

I do solemnly and sincerely declare that:

- (1) I am the sole author/writer of this Work;
- (2) This Work is original;
- (3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
- (4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
- (5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya (“UM”), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
- (6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate’s Signature

Date

Subscribed and solemnly declared before,

Witness’s Signature

Date

Name:

Designation:

ABSTRAK

Mini hidro loji janakuasa (MHPP) DG berasaskan kos sumber yang berkesan dan mesra alam untuk skim bekalan elektrik luar bandar. Walau bagaimanapun, isu teknikal yang disebabkan dengan DG adalah kejadian yang sengaja Islanding dalam sistem. Islanding mempunyai kelebihan yang besar seperti peningkatan kebolehpercayaan, pengurangan blackout. Walau bagaimanapun, operasi Islanding adalah satu isu yang mencabar, jika ada apa-apa yang tidak seimbang antara permintaan beban dan penjanaan kuasa, kekerapan sistem akan berubah. Kekerapan sistem dikekalkan dengan mengawal kelajuan turbin melalui gabenor. Jika gabenor gagal untuk menstabilkan kekerapan, load shedding teknik perlu digunakan untuk mengekalkan kestabilan dan keselamatan rangkaian pengedaran. PID gabenor berasaskan mempunyai masalah mendapatkan penalaan parameter yang optimum. Untuk mengatasi ini, teknik kawalan logik kabur boleh menjadi satu pilihan untuk memberikan kawalan yang mantap dan cepat.

Kajian ini mencadangkan gabenor berasaskan kabur untuk kawalan frekuensi beban (LFC) MHPP, dan membandingkan tindak balas dengan gabenor berasaskan PID untuk menunjukkan kelebihan. Selain daripada itu, kajian ini mencadangkan kabur berdasarkan di bawah skim penumpahan beban kekerapan (UFLS) diaplikasikan dalam rangkaian pengedaran islanded yang berkaitan dengan DG. Yang dicadangkan di bawah skim menumpahkan beban kekerapan terdiri daripada beban logik kabur menumpahkan pengawal (FLLSC) dan beban susut pengawal modul (LSCM). FLLSC menganggarkan jumlah ketidakseimbangan kuasa dan menghantar nilai ini LSCM untuk menumpahkan beban yang diperlukan. Kedua-dua berasaskan Peristiwa Response berdasarkan kes menumpahkan di bawah beban kekerapan dimodelkan dan diuji ke atas beban asas dan kapasiti beban puncak.

ABSTRACT

Mini hydro power plant (MHPP) based DG is cost effective and environmental friendly resource for rural electrification schemes. The DG can be connected in parallel with grid to supply the increased load demand. However, in utility practice when load disturbance occurs in grid, DG is tripped-off. Due to this, DG capacity is not utilized efficiently. In order to utilize the DG capability, islanding need to be done. The islanding has a considerable advantage such as reliability improvement, blackout reduction. However, islanding operation is a challenging issue; if there is any unbalanced between load demand and power generation, the system frequency will change. The system frequency is maintained by controlling the turbine speed through governor. If governor fail to stabilize the frequency, load shedding techniques needs to be applied in order to maintain distribution network stability and security. PID based governor have the problem of obtaining optimum parameter tuning. In order to cope this, fuzzy logic control technique may be an option to provide robust and quick control.

This research proposes fuzzy based governor for load frequency control (LFC) of MHPP, and compares its response with PID based governor to show its superiority. Apart from this, this research proposes a fuzzy based under frequency load shedding (UFLS) scheme applied in an islanded distribution network connected with DG. The proposed under frequency load shedding scheme consists of a fuzzy logic load shedding controller (FLLSC) and load shed controller module (LSCM). FLLSC estimates amount of power imbalance and sends this value to LSCM for shedding the required load. Both Event-based and Response based under frequency load shedding cases are modelled and tested on base load and peak load capacity. The fuzzy based under frequency load shedding scheme is designed to shed optimal load in the system.

ACKNOWLEDGMENTS

All praise to Almighty ALLAH SWT with his blessing all good deeds completes. With blessing of Almighty ALLAH, prayers of my parents and kind supervision and guidance of my respected supervisor, ALHAMDULILLAH I become able to complete this thesis.

I would like to acknowledge special thanks to my respected supervisor Dr. Hazlie Mokhlis. I learn everything about research from him. He supervised and guided me during every stage of my study. He took my hand in the field of research at that time when I did not know how to walk in the field of research. He trusted upon me at that time when I myself was not confident enough for doing research. I choose research as my life career by inspiring from his professional attitude. I feel myself fortunate enough to work under his supervision and still it is my life desire to continue my PhD under his supervision.

I wish to thank Mr. Mazaher Karimi for his technical support throughout my Master study.

I wish to express my deepest gratitude to my parents for their support and sacrifice of living without me for long time. I would like to thank my brothers, sisters, my wife and my friends for their encouragement and support.

TABLE OF CONTENTS

	Page No.
TITLE PAGE	i
ORIGINAL LITERARY WORK DECLARATION	ii
ABSTRAK	iii
ABSTRACT	iv
ACKNOWLEDGEMENT	v
TABLE OF CONTENTS	vi
LIST OF FIGURES	x
LIST OF TABLES	xiv
LIST OF SYMBOLS AND ABBREVIATIONS	xvi
1. INTRODUCTION	1
1.1 Introduction	1
1.2 Overview of Load Frequency Control and Load Shedding Scheme	2
1.3 Problem Statement	4
1.4 Objectives and Scope of Work	4
1.5 Research Methodology	5
1.6 Dissertation Outline	6

2. DISTRIBUTED GENERATION, GOVERNOR CONTROL METHODS AND FUZZY LOGIC CONTROL: AN OVERVIEW	8
2.1 Introduction to Distributed Generation (DG)	8
2.2 DG Modes of Operation	8
2.2.1 Parallel Mode Operation	9
2.2.2 Islanded Mode Operation	10
2.3 Mini Hydro Power Plant Type DG Working Principle	11
2.4 Hydro Governor Controllers	12
2.4.1 Conventional Governor Control Methods	13
2.4.1.1 Limitations of PID Controller	14
2.4.2 Alternative Control Methods	14
2.4.3 Intelligent Control Methods	16
2.5 Introduction to Fuzzy Logic Control	17
2.5.1 Fuzzification	18
2.5.2 Rule Base and Inference Mechanism	18
2.5.3 De-fuzzification	19
3. LOAD SHEDDING TECHNIQUES: AN OVERVIEW	20
3.1 Importance of Frequency Balance and Control	20
3.2 Power System Swing Equation	21
3.3 Abnormal Frequency and Voltage in Power System	23
3.4 Load Shedding Schemes and its Types	25
3.4.1 Under Frequency Load Shedding Techniques	26
3.4.1.1 Conventional Load Shedding Techniques	27

3.4.1.2	Adaptive Load Shedding Techniques	28
3.4.1.3	Intelligent Load Shedding Techniques	28
3.4.2	Response Based and Event Based Methods	29
3.5	Load Shedding Techniques in Transmission Network	30
3.6	Load Shedding Techniques in Distribution Network	31
4.	PROPOSED LOAD FREQUENCY CONTROL AND UNDER FREQUENCY LOAD SHEDDING SCHEME FOR ISLANDED MODE	33
4.1	Overview of Proposed Load Shedding Scheme	34
4.2	Methodology for Proposed UFLS Scheme	35
4.2.1	FLLSC for Event Based Case	38
4.2.2	FLLSC for Response Based Case	38
4.3	Modelling of fuzzy based governor in PSCAD	39
4.4	Fuzzy logic Load Shedding Controller (FLLSC) Model in PSCAD	44
4.5	Exciter System Model	49
4.6	Hydraulic Turbine and Governor Model	50
4.7	Synchronous Generator Parameters	54
4.8	Load Modelling and Under Ground Cable Parameters	57
5.	RESULTS AND DISCUSSIONS	61
5.1	Test System for the Proposed Fuzzy Based LFC and UFLS Scheme	61
5.2	Case Studies	68
5.2.1	Case I: Load Frequency Control	69

5.2.1.1	10% - 25% Load Disconnected	69
5.2.1.2	10% - 25% Load Connected	70
5.2.2	Case II: Event Based Load Shedding	73
5.2.2.1	Event Based at Base Load Capacity	73
5.2.2.2	Event Based at Peak Load Capacity	79
5.2.3	Case III: Response Based Load Shedding	83
5.2.3.1	Response Based at Base Load Capacity	83
5.2.3.2	Response Based at Peak Load Capacity	89
5.2.4	Case IV: Event Based and Response Based Load Shedding	93
5.2.4.1	Event Based and Response Based at Base Capacity	93
5.2.4.2	Event Based and Response Based at Peak Capacity	98
5.3	Overall Observation	102
6.	CONCLUSION AND FUTURE WORK	104
6.1	Summary	104
6.2	Future Work	106
	REFERENCES	107

LIST OF FIGURES

	Page No.
Figure 2.1 Different DG resources connected with grid operating in parallel mode	9
Figure 2.2 Islanded distribution network connected to DG	10
Figure 2.3 Block diagram of mini hydro power plant	12
Figure 2.4 Block diagram of Mini hydro power plant with dump load	15
Figure 2.5 Block diagram of Fuzzy logic controller	17
Figure 2.6 Membership function MN (more negative) of input frequency error	18
Figure 4.1 Proposed load shedding scheme layout	35
Figure 4.2 Flow chart of proposed load shedding scheme	36
Figure 4.3 Block diagram of proposed fuzzy based governor	39
Figure 4.4 Snapshot of frequency error fuzzification at certain time instant	40
Figure 4.5 Frequency error membership functions	41
Figure 4.6 Load membership functions	41
Figure 4.7 Turbine gate membership functions	41
Figure 4.8 Block diagram of fuzzy logic load shedding controller	45
Figure 4.9 Frequency membership functions	46

Figure 4.10 Rate of change of frequency (df / dt) membership functions	46
Figure 4.11 Lshed (p.u.) membership functions	46
Figure 4.12 Fuzzy logic load shedding controller with LSCM module	48
Figure 4.13 Transfer function of IEEE type AC1A excitation system model	49
Figure 4.14 Block diagram of turbine speed control with governor	51
Figure 4.15 Block diagram of Electro-Hydraulic PID based governor	51
Figure 4.16 Synchronous generator model with PID based governor in PSCAD	54
Figure 4.17 Synchronous generator model with fuzzy based governor in PSCAD	55
Figure 5.1 Mini hydro power plants connected to islanded distribution network	62
Figure 5.2(a) LFC test system with PID based governor	63
Figure 5.2(b) LFC test system with fuzzy based governor	64
Figure 5.3(a) Test system with fuzzy based governor and UFLS scheme	66
Figure 5.3(b) Test system with PID based governor and UFLS scheme	67
Figure 5.4 Frequency responses at 10 % - 25 % load reduction	69
Figure 5.5 Frequency responses at 10 % - 25 % load addition	71
Figure 5.6 Frequency overshoot graph at different load reduction	72
Figure 5.7 Frequency undershoot graph at different load addition	72

Figure 5.8 Event based case when load shedding scheme is not applied	74
Figure 5.9 Frequency response during event based at base capacity	75
Figure 5.10 Voltage graph during Event Based at Base capacity (PID governor)	76
Figure 5.11 Voltage graph during Event Based at Base capacity (fuzzy governor)	76
Figure 5.12 Power graph during Event based at base capacity	77
Figure 5.13 Breakers operated during Event based at base capacity	78
Figure 5.14 Frequency response during Event based at peak capacity	79
Figure 5.15 Power graph during Event based at peak capacity	80
Figure 5.16 Voltage graph during Event Based at Peak capacity (PID governor)	81
Figure 5.17 Voltage graph during Event Based at Peak capacity (fuzzy governor)	81
Figure 5.18 Breakers operated during Event based at peak capacity	82
Figure 5.19 Response based case when load shedding scheme is not applied	84
Figure 5.20 Frequency response during Response based at base capacity	85
Figure 5.21 Voltage graph in Response Based at Base capacity (PID governor)	86
Figure 5.22 Voltage graph in Response Based at Peak capacity (fuzzy governor)	86
Figure 5.23 Power graph during Response based at base capacity	87
Figure 5.24 Breakers operated during Response based at base capacity	88

Figure 5.25 Frequency response during Response based at peak capacity	89
Figure 5.26 Voltage graph in Response Based at Peak capacity (PID governor)	90
Figure 5.27 Voltage graph in Response Based at Peak capacity (fuzzy governor)	90
Figure 5.28 Power graph during Response based at peak capacity	91
Figure 5.29 Breakers operated during Response based at peak capacity	92
Figure 5.30 Frequency response for Event and Response based at base load capacity	93
Figure 5.31 Power graph for Event and Response based at base load capacity	94
Figure 5.32 Voltage in Event and Response Based at Base capacity (PID governor)	95
Figure 5.33 Voltage in Event and Response Based at Base capacity (fuzzy governor)	95
Figure 5.34 Breakers operated during Event and Response based at base capacity	96
Figure 5.35 Frequency response for Event and Response based at peak load capacity	98
Figure 5.36 Power graph for Event and Response based at peak load capacity	99
Figure 5.37 Voltage in Event and Response Based at Peak capacity (PID governor)	100
Figure 5.38 Voltage in Event and Response Based at Peak capacity (fuzzy governor)	100
Figure 5.39 Breakers operated during Event and Response based at peak capacity	101

LIST OF TABLES

	Page No.
Table 4.1 Rule table for fuzzy based governor	43
Table 4.2 Rule table for fuzzy logic load shedding controller (FLLSC)	47
Table 4.3 Sample data of IEEE AC1A excitation model parameters	50
Table 4.4 Value of governor model parameters	52
Table 4.5 Value of hydro turbine parameters	53
Table 4.6 Synchronous generator parameters	56
Table 4.7 Transformer parameters	57
Table 4.8 Static load parameters	59
Table 4.9 Cable specification	59
Table 4.10 Load values and ranking table	60
Table 5.1 Description of case studies for LFC and UFLS scheme	68
Table 5.2 Optimum load shedding values during event based at base capacity	78
Table 5.3 Optimum load shedding values during event based at peak capacity	83
Table 5.4 Optimum load shedding values during response based at base capacity	88
Table 5.5 Optimum load shedding values during response based at peak capacity	92

Table 5.6 Optimum load shedding values in event and response based at base capacity 97

Table 5.7 Optimum load shedding values in event and response based at peak capacity 102

LIST OF SYMBOLS AND ABBREVIATIONS

f	Frequency
df/dt	Rate of change of frequency
P	Active Power
Q	Reactive Power
S	Complex Power
T_{mech}	Mechanical Torque
T_{elec}	Electrical Torque
P_{mech}	Mechanical Power
P_{elec}	Electrical Power
J	Moment of Inertia
ω	Angular velocity
ΔP	Power imbalance
H	Generator Inertia Constant
Δf	Frequency error
DG	Distributed Generation
LFC	Load Frequency Control
FLLSC	Fuzzy Logic Load Shedding Controller

LSCM	Load Shed Controller Module
UFLS	Under Frequency Load Shedding
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
TNB	Tenaga Nasional Berhad

CHAPTER 1

INTRODUCTION

1.1 Introduction

Presently, Distributed Generation's (DG's) penetration in power system network is increasing around the world. For example, in Europe 10% of its electricity is generated from combined heat power based DG (Puchala, et al.). Meanwhile, Malaysia has also started its initiatives in 9th Malaysia Plan to utilize renewable energy resources for electricity generation. In this plan, Malaysia is targeting to achieve 6% renewable energy usage by 2015 and 11% by the end of 2020 (Hashim & Ho, 2011). This shows increasing trend of DG technologies which may lead to its commercialization all around the world.

A DG may be any small type of electrical power generation installed in a distribution system having capacity less than 10MW (Barker & De Mello, 2000). DG can comprise of any renewable energy source like wind turbine, photovoltaic array, micro turbine, fuel cells, conventional diesel and natural gas reciprocating engines. A DG of Mini hydro power plants have been also connected to the grid, mainly in rural area. These plants are cost-effective since it does not require dam and water storage. Furthermore, it is environmental friendly.

Despite of advantages that a DG based Mini hydro has, its implementation in a power system network can cause various problems to existing network mainly on safety and security of the system. One of the problems exists that presents when a distribution network connected with DG is electrically isolated from main grid. This isolation can be due to load disturbance such as occurrence of fault in the grid. The network is called islanded system.

In practice, when this condition happens, DG is disconnected from the power system due to safety of the maintenance crew and security of the system. This is necessary in order to avoid power collapse and blackout in the system. When islanding occurs in a distribution network, voltage and frequency are severely disturbed due to imbalance between generation and load demand. In order to utilise DG during islanded mode, an effective controller is needed to stabilise the frequency (Walling & Miller, 2002).

1.2 Overview of Load Frequency Control and Load Shedding Scheme

Mini hydro type of DG usually supplies electricity to islanded networks or to grid. Mini hydro power plants (MHPP) are complex and nonlinear power systems. Hence, in these power plants, frequency and voltage of the system varies continuously. These power plants employ different control techniques for maintaining the voltage and frequency within specific range. Voltage is controlled through excitation control and frequency is controlled by making generation equal to load demand using governor control. There are different types of governor used for controlling the frequency. Basic function of governor is to control the generator speed to keep its frequency constant. Conventionally, mechanical hydraulic governor, Electro-hydraulic PI and PID governor are employed for load frequency control of mini-hydro power plant (Culberg, et al.).

Mechanical hydraulic governor due to its slow response is not suitable for today's complex power system involving sharing of distributed generation. PID based governor also encountered the problem of parameter tuning. Incorrect tuning of PID based governor may cause failure to control frequency during transient conditions. The intelligent control techniques e.g. fuzzy logic control technique, due to their robustness may be an option to

these problems. Power system network also encounters generation losses or sudden load increment cases. To cope with this, load shedding technique is required to stabilize the frequency and preventing power system from blackouts.

The primary reason for under-frequency load shedding implementation in power system includes:

- Lack of sufficient power supply.
- Lack of sufficient distribution load carrying ability.

The power system encountered these problems due to:

- Faster increase in load demand than generator supply to accomplish the demand.
- Abnormally high unforeseen demands that are created by unusual changes or by some special events (sudden load increment and nature of load) that cause a significant loss in diversity of consumers' loads.
- Overloading or Failure in some element or elements of the supply facilities such as generator tripping and transformer failure.

In this research, load shedding implies decreasing load at the bus bar. Load shedding helps to bring back the power balance in system and prevent voltage and frequency decay. In addition, load shedding can even restore a lower voltage and frequency into acceptable range.

1.3 Problem statement

There are two approaches to control the frequency; first approach is to use governor for frequency control during normal operation of mini hydro DG, second approach is to apply load shedding schemes for frequency control during system failure or overloading cases. Frequency can be maintained by controlling the turbine speed. Commonly, PID controllers are used in governor for controlling turbine speed. However, conventional PID controllers may fail in controlling complex systems due to un-optimum P, I, D parameter setting. Furthermore, the response of PID controller also could be slow if the parameter setting is not correct. Hence, an intelligent method that can be easily used and able to response fast can be an option to PID controller.

Load shedding through frequency relay is the most common type of under frequency load shedding (UFLS) technique for frequency control under abnormal conditions. In this technique, under frequency relay will operate when system frequency falls below a certain threshold, and shed some amount of electrical power in step-wise manner. This UFLS technique cannot ensure system security and reliability, since the amount of load to be shed may not be optimized. For this purpose, an intelligent Under Frequency Load Shedding scheme is required for islanded distribution network connected with Mini hydro.

1.4 Objectives and Scope of Work

In this work, an islanded distribution network connected with DG type of Mini-hydro power plant is considered for the studies. Apart from this, this study considers fuzzy logic control technique for load frequency control (LFC) and under frequency load shedding

(UFLS) scheme. Fuzzy logic control technique due to its robustness has the advantage of dealing with complex system easily. Considering the importance of frequency control for islanded network, following are the main objectives of this work:

- (1) To develop a fuzzy based load frequency control (LFC) for islanded distribution network connected with mini hydro power plant.
- (2) Compare fuzzy based governor and PID based governor for load frequency control (LFC).
- (3) To develop the fuzzy based under frequency load shedding (UFLS) scheme for stable operation of islanded distribution network.

1.5 Research Methodology

In order to achieve the above mentioned objectives, following research methodology will be carried out.

- (1) Review all existing techniques applied for load frequency control and under frequency load shedding scheme for mini hydro power plant.
- (2) Model a distribution network using PSCAD/EMTDC software v4.2.1.
- (3) Model fuzzy based governor in PSCAD/EMTDC software for load frequency control that should have best response in term of settling time, over shoot and undershoot.
- (4) Incorporate fuzzy based governor into the distribution network and test its performance.
- (5) Compare fuzzy based governor with PID based governor for load frequency control (LFC) to show its superiority.

- (6) Model fuzzy logic load shedding controller (FLLSC) and load shed controller module (LSCM) in PSCAD/EMTDC software for load shedding scheme.
- (7) Test proposed UFLS scheme on Distribution Network.
- (8) Incorporate PID based governor into the distribution network and test its performance with proposed UFLS scheme.
- (9) Incorporate fuzzy based governor into the distribution network and test its performance with proposed UFLS scheme.
- (10) Compare fuzzy logic based response with PID based governor response during under-frequency load shedding scheme (UFLS) implementation.

1.6 Dissertation Outline

This dissertation consists of six chapters.

Chapter 1: Introduction provides the importance of load frequency control and under frequency load shedding in DG. It provides the overview of load frequency control and under-frequency load shedding scheme. The objectives of study are presented followed by research methodology. Dissertation outline is given at the end of this chapter.

Chapter 2: Distributed Generation, Governor Control Methods and Fuzzy Logic Control: An Overview will discuss about Distributed generation, basic principle of mini hydro, existing conventional, alternative and intelligent LFC techniques. In the end, introduction about fuzzy logic control is presented.

Chapter 3: Load Shedding Techniques: An Overview will discuss the importance of frequency control followed by power swing equation. This chapter presents the overview of

conventional, adaptive and intelligent types of load shedding schemes implemented on transmission and distribution network operating in islanding mode. Event based and response based protection are also discussed in the chapter.

Chapter 4: Proposed Load Frequency Control and Under-Frequency Load Shedding Scheme for Islanded Mode will describe the methodology of proposed scheme for LFC as well as under-frequency load shedding scheme. The mathematical modelling of exciter, governor (PID as well as fuzzy logic based), fuzzy logic load shedding controller and load shedding controller module, hydraulic turbine, synchronous generator and distribution network are presented. Their algorithms are also presented in this chapter.

Chapter 5 Results and Discussions provides modelling of test system with distribution network of Malaysia designed in PSCAD/EMTDC v.4.2.1 software. This chapter also presents the major contributions of this research. Different cases of load frequency control and under-frequency load shedding scheme carried out in islanding mode are presented with discussion and comparison.

Chapter 6 Conclusion and Future Work describes the research conclusion and some recommendations for future work to improve the research.

CHAPTER 2

DISTRIBUTED GENERATION, GOVERNOR CONTROL METHODS AND FUZZY LOGIC CONTROL: AN OVERVIEW

2.1 Introduction to Distributed Generation (DG)

Distributed Generation (DG) can be any small scale of electrical power generation technology that supplies electric power to the load site. The generation capacity of a DG is usually less than 10MW (Puchala, et al.). DG based power plants are smaller in capacity than central generating plants so as to allow interconnections at nearly any point in a power system. DG can be operated both as grid connected as well as islanded mode.

A DG system in the distribution network designed must be able to operate successfully in both grid connected mode and islanded mode. Presently, DG islanding mode operation is strictly prohibited. It should be noted that during islanding operation, voltage and frequency are very sensitive in distribution network. When such an islanding situation occurs, the power generation must be capable of maintaining stability, reliability and power quality, ensuring customers voltage and frequency at acceptable range.

2.2 DG Modes of Operation

Distributed generation can be operated by one of the following two modes (Borbley, 2001):

- Distributed resources configured to operate in parallel with grid. This mode of operation is known as utility interactive.
- Distributed resources configured to operate independently from the grid. This mode of operation is called premeditated islanded mode.

2.2.1 Parallel Mode Operation

In parallel mode operation, DG is connected to grid and becomes part of overall system as illustrated in Figure 2.1. In this case, the DG and network should be protected and controlled as an integrated system.

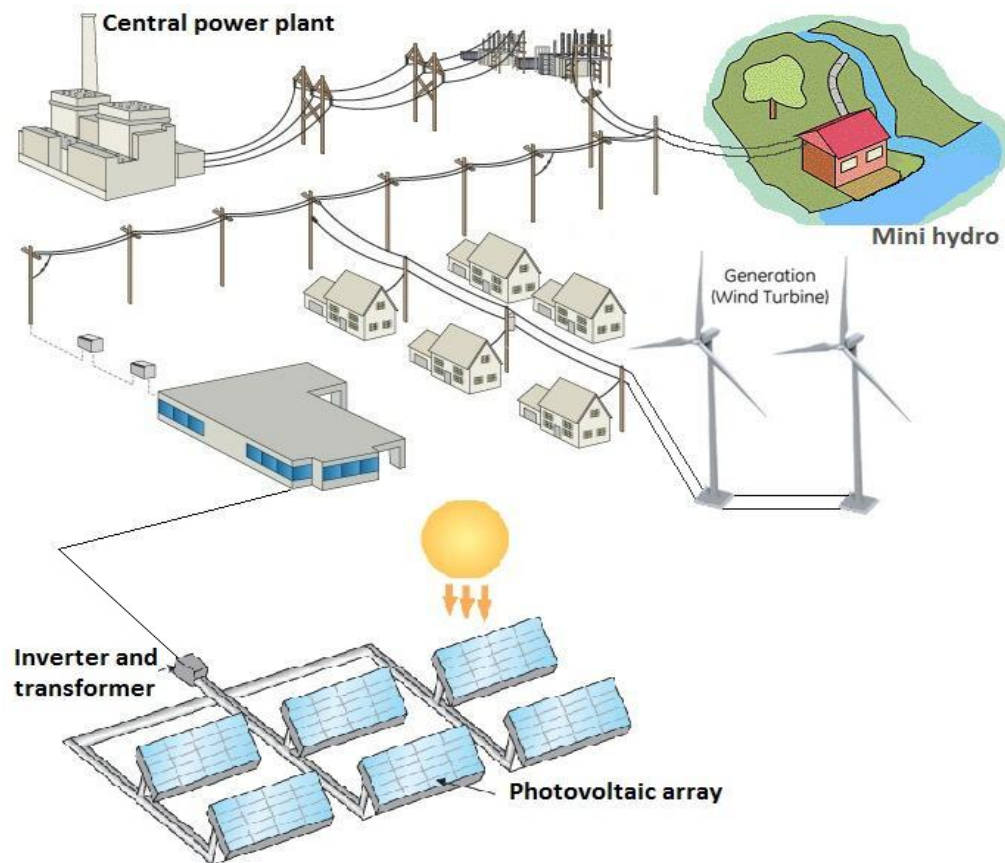


Figure 2.1 Different DG resources connected with grid operating in parallel mode

2.2.2 Islanded Mode Operation

According to IEEE standard, islanding mode operation is defined as “A condition in which a portion of utility system that contains both load and distributed resources remains energized while isolated from the remainder of the utility system” (“IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems,” 2000).

Islanding can occur due to power system imbalance like fault, line and generator outages. When islanding occurs, distribution network is disconnected from the main grid through circuit breaker operation. The remaining independent islanded area can operate if DG sources are connected (Dola & Chowdhury, 2006). Figure 2.2 illustrates this case when system is disconnected from the main grid.

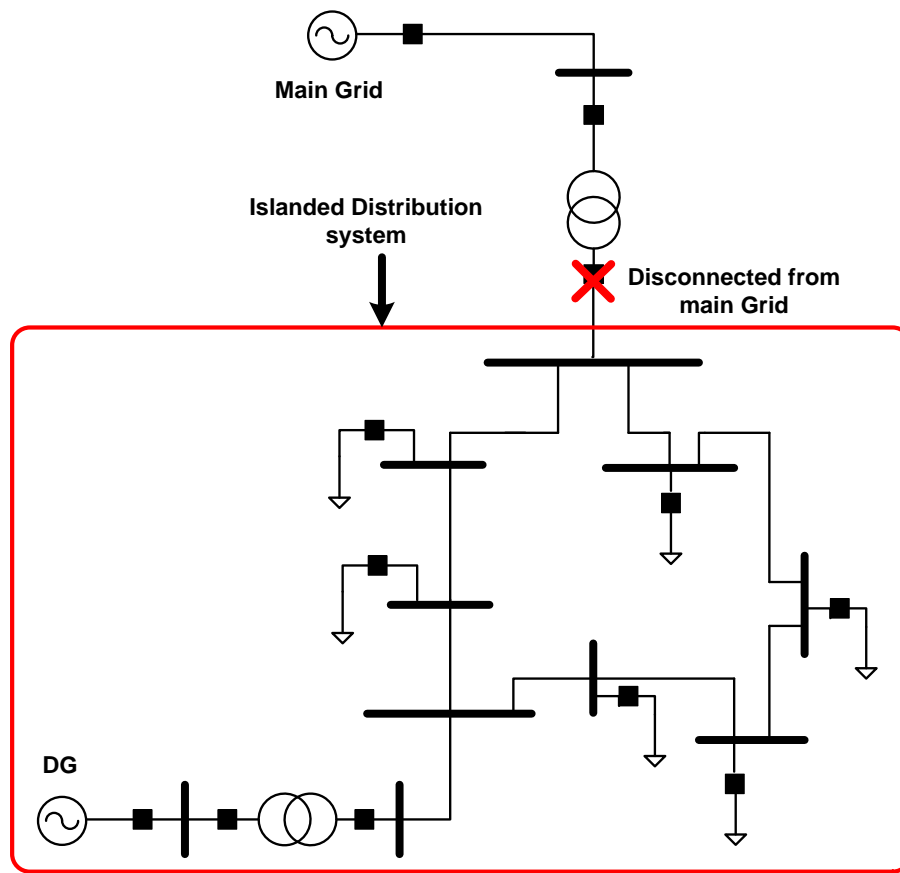


Figure 2.2 Islanded distribution network connected to DG

Implementation of islanding mode is more difficult than parallel mode with grid, as it considers generation and load matching for ensuring the voltage and frequency within acceptable range. The balance between generation and consumption is really a challenging task in an islanded network. Frequency will increase if the generation exceeds load demand and will decrease if overloading occurs. Spinning reserve can be used to recover the system voltage and frequency. However, if the load is more than the total generation during islanding mode, load shedding process is essential for maintaining the stability and security of distribution network.

2.3 Mini Hydro Power Plant Type DG Working Principle

The DG for islanding operation in this research consists of mini hydro power plant. This section provides a brief description of mini hydro power plant and its basic components. Mini hydro power plant mainly consists of a small reservoir or irrigation canal, governor, turbine and generator as illustrated in Figure 2.3. The water is passed from reservoir to turbine through penstock. When water strikes at the turbine blades, it converts hydraulic energy into mechanical energy. Water flow in the turbine is controlled through governor. Main function of governor is to control generator speed to keep its frequency constant. Gate position of turbine is controlled through servomotor, which adjusts water flow to produce power according to load connected.

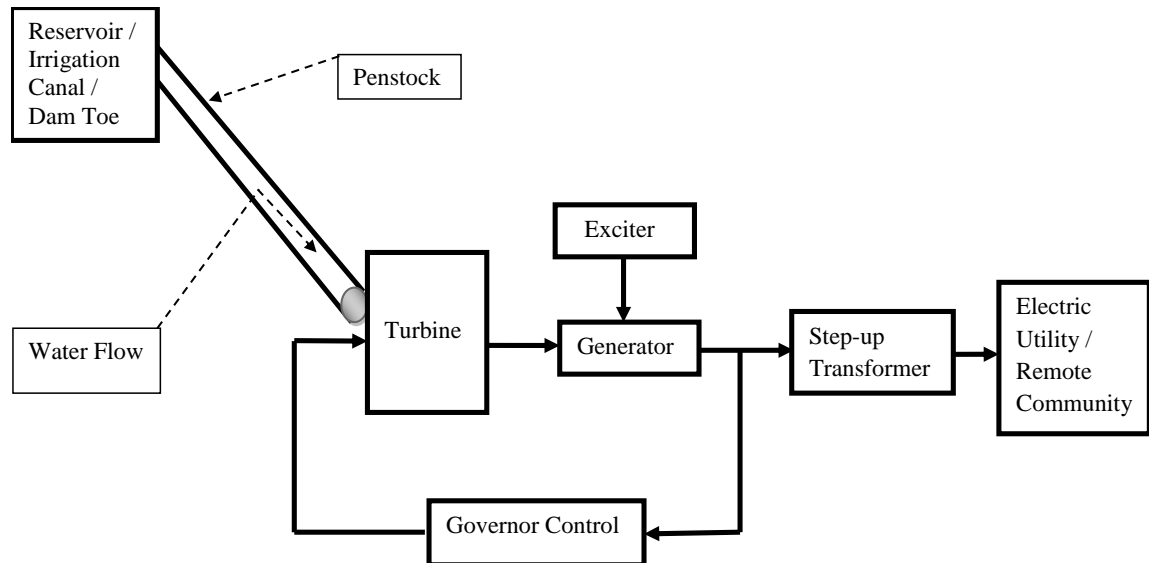


Figure 2.3 Block diagram of mini hydro power plant

Rotating turbine turns the rotor inside generator through mechanical shaft. Field winding of synchronous generator is excited by supplying direct current through exciter which produces the magnetic field. This magnetic field induces alternating current in the stator when rotor moves through turbine. The generated power is stepped-up through step-up transformer and then supplied to utility or remote community through transmission system. In power conversion process, frequency of system is controlled by turbine speed. Hence, frequency can be varied by varying input mechanical power (Kundur, 1994).

2.4 Hydro Governor Controllers

Different control techniques of hydro governor are needed for maintaining frequency within acceptable range. In the past, mechanical hydraulic governor were applied for this purpose which is now replaced by electro hydraulic PI/PID governor and enhanced

governor. Fundamental mathematical models of all these governors and turbine suitable for hydro electric power plant are discussed in ("Hydraulic turbine and turbine control models for system dynamic studies," 1992) and (Report, 1973).

2.4.1 Conventional Governor Control Methods

Conventionally, mechanical hydraulic and electro-hydraulic PI and PID governor are employed for speed control. PID controllers are very suitable for governor control because it provides three functions to control the system. The proportional, integral and derivative function provide reduction in rise time, zero steady state error and reduced oscillation respectively, enabling system to respond quickly during load disturbances. PID and PI controllers best deals with linear models and are suitable for second order systems. Such application is discussed by I. Salhi where he applied PI controller technique on Micro Hydro Power Plant prototype for load frequency control (Salhi, et al., 2008). Despite of having many advantages, PID controllers suffer from problem of obtaining optimum parameter tuning. PID controllers fail to provide satisfactory control to non-linear systems having severe problem of integrator wind-up (Atherton & Majhi, 1999; Culberg, et al.).

To solve this problem, different techniques have been proposed. Poulin & Pomerleau proposed a novel method by using constant M circles in Nicholas chart for obtaining PI / PID controller's parameters. The concept behind this technique was that maximum overshoot of system response should remain in a pre-determined value followed by a step change in original input. Proposed technique is known as Maximum Peak resonance specifications (MPRS) technique. Pre determined phase margin and bandwidth ensures the system stability (Poulin & Pomerleau, 1997). Later this technique was modified and

applied first time in power systems by Khodabakhshian. In this technique a new PID load frequency controller is designed for a single machine infinite bus hydro system as well as for automatic generation control of hydro power plant in multi machine system. Stability and dynamic of this controller has shown enhanced damping of power system and better performance over conventional PI controller (Khodabakhshian & Golbon, 2005; Khodabakhshian & Hooshmand, 2010).

2.4.1.1 Limitations of PID controller

Despite of the PID controller's advantages, these controllers have encountered with problem of parameter tuning and fail to provide satisfactory control of frequency over transient conditions. In order to overcome these problems, fuzzy logic control can be applied, as it provides robust control of frequency over wide variation of load. Several researchers have implemented fuzzy logic technique on load frequency control. Fuzzy logic technique applied for LFC shows only the competency of fuzzy logic to withstand these frequency problems. However it is not compared with PID / PI controller to show its superiority. Minimum time taken by frequency to become stable was greater than 60 sec which is even worse than the worst response of PID /PI controller (Hanmandlu & Goyal, 2008).

2.4.2 Alternative Control Methods

Apart from conventional control methods, some authors have proposed different alternative control methods to stabilize the frequency variation. One way to control

frequency variation is to employ ballast/ dump load (Henderson, 1998; Ranjitkar, et al., 2006). Dump load consists of high resistors used to dissipate the load in order to protect the generator. Operation of dump load can be controlled with electronic load governor (ELG). ELG consists of electronic device that control frequency by automatically varying ratio of actual load and dump load to keep constant load on generator. The ballast/ dump load concept is illustrated in Figure 2.4.

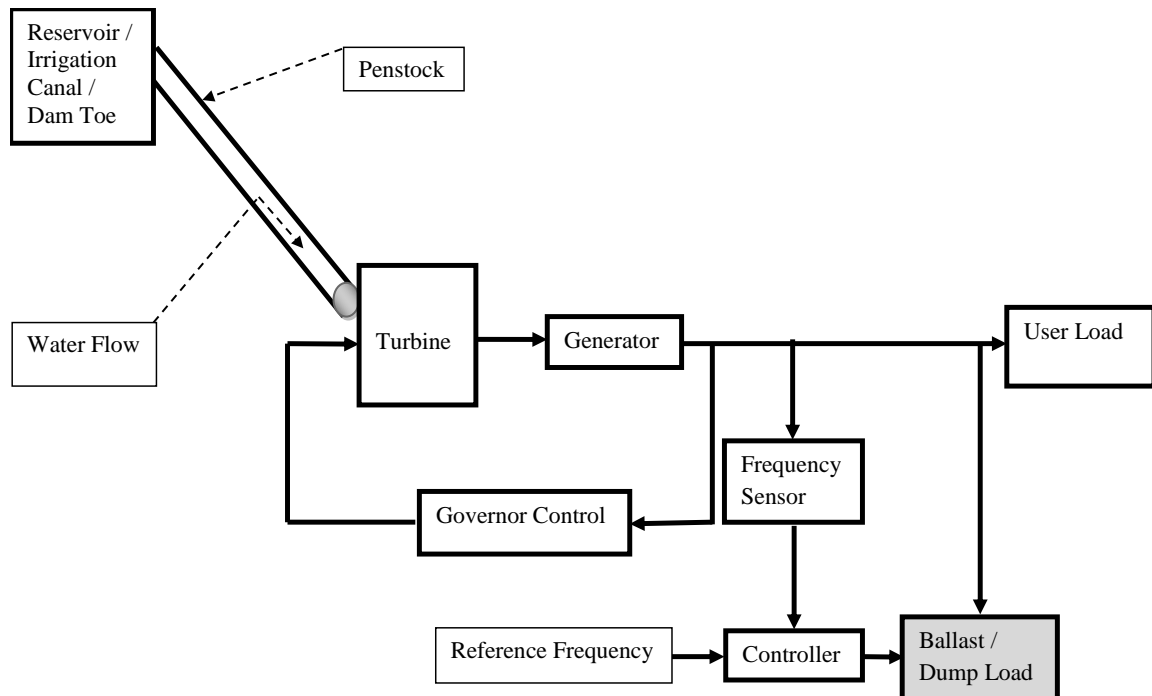


Figure 2.4 Block diagram of Mini hydro power plant with dump load

Dump load ensures frequency control within range; however, it dissipates a large amount of generated power because of load variation. Efforts have been made to reduce the amount of dissipated power as much as possible by dump load. Doolla & Bhatti proposes a new cost-effective technique for load frequency control by reducing the size of dump load (Doolla & Bhatti, 2006).

2.4.3 Intelligent Control Methods

Many researchers have implemented intelligent control techniques including fuzzy logic control, Neuro-fuzzy and artificial neural networks for robust control of frequency operating in islanded mode. In this regard, I. Salhi et al. implemented fuzzy logic control for load frequency control in micro hydro power plant based on Mamdani inference system and Tekagi-Sugeno inference system. In these papers, two fuzzy sets are performed, one is fuzzy controller which maintains frequency variations and regulates waste of available water on reservoir. The second set is fuzzy supervisor which controls electrical production between departures because the mini grid is divided into three sub-networks (departures) that are powered by the order of preference. This method provides cost effective solution for providing electricity to those near to mountains (I. Salhi, et al., 2010a, 2010b; Issam Salhi, et al., 2010).

An advanced controller consisting of four control schemes for dividing control action into nonlinear and linear parts which shows best response over other controllers is presented in (Hanmandlu & Goyal, 2008; Hanmandlu, et al., 2006). The implementation of this technique on small hydro power plant yields approximately same results as from simulation. The linear part is formed by adaptive fast transversal filter (FTF) algorithm and Normalized least mean square (LMS) algorithm. Fuzzy PI and Neural Network form nonlinear part. The proposed technique is compared with six other techniques and resulted in lowest undershoot, overshoot and smaller settling time to all other techniques.

2.5 Introduction to Fuzzy Logic Control

Fuzzy logic control was introduced by Lotfi Zadeh in 1965 (Singh & Rattan, 2003). It is a mathematical tool for dealing with uncertainty. The word fuzzy means “not clear, distinct or precise”. In general, fuzzy logic control provides an inference structure that enable appropriate human reasoning capabilities. On the contrary, traditional binary set theory describes crisp events, events that either do or do not occur. Fuzzy logic controllers are suitable to model a system which is too complex and not well defined by mathematical formulation. Fuzzy logic controllers represent the expert human knowledge in terms of linguistic variables that are called fuzzy rules (Ozbay & Gencoglu, 2010). The basic block diagram of fuzzy logic controller is shown in Figure 2.5.

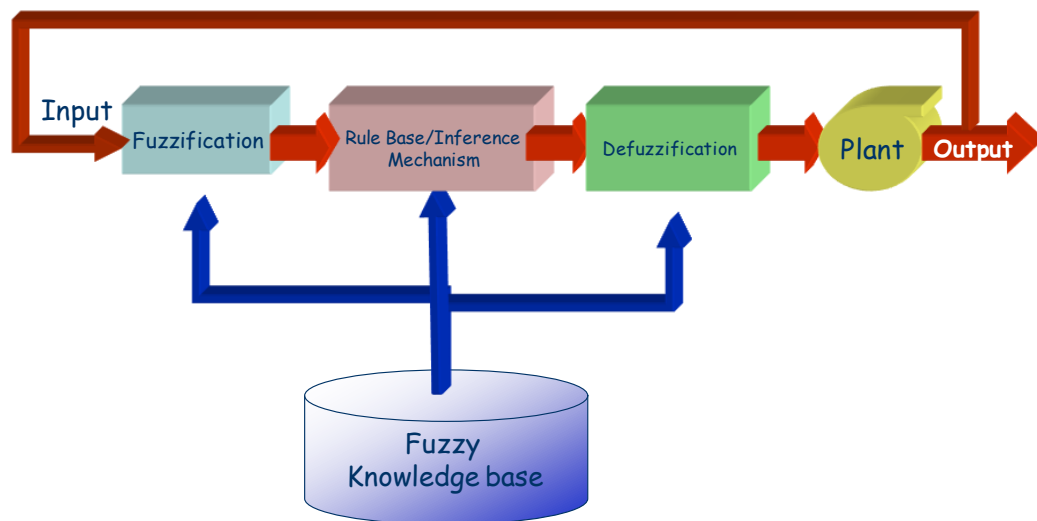


Figure 2.5 Block diagram of Fuzzy logic controller

Fuzzy logic controllers are mainly consists of fuzzification, Rule base and inference mechanism, and De-fuzzification steps. Each step is described briefly in the following sections.

2.5.1 Fuzzification

In fuzzification, the real input values are converted into fuzzy set values, assigning degree to these inputs belong to each of the appropriate fuzzy sets. Fuzzification is carried out by characterizing the fuzzy input into its membership functions. Membership function classifies input element as discrete or continuous in the set. Graphically membership functions can be of different shapes e.g. triangular shape, trapezoidal shape, bell shape, and Gaussian shape. These membership functions can be used depending upon the system behaviour. However, triangular and trapezoidal membership functions are frequently used in engineering applications. Figure 2.6 shows one triangular membership function of an input (frequency error) to a fuzzy logic control.

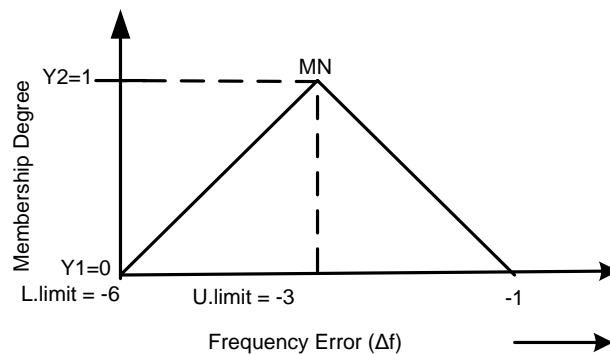


Figure 2.6 Membership function MN (more negative) of input frequency error

2.5.2 Rule Base and Inference Mechanism

Rule base of fuzzy logic controller contains expert's linguistic descriptions expressed in the form of logical implications. Rule base is applied in the form of IF-THEN rule to assign the input output control such as:

IF frequency is low and load is high THEN open turbine gate.

Inference mechanism evaluates the active signals for taking control actions from fuzzy rules.

2.5.3 De-fuzzification

De-fuzzification is carried out to convert the fuzzy linguistic variable into real crisp values. Without de-fuzzification, results of fuzzy logic generated cannot be used in applications. De-fuzzification is carried out through various methods such as; centre of gravity, weighted average and maximum mean methods.

CHAPTER 3

LOAD SHEDDING TECHNIQUES: AN OVERVIEW

Under-frequency load shedding (UFLS) scheme is applied when power system generation is not sufficient to meet the increase of load demand. Under-frequency load shedding scheme is applied for maintaining stability within the system. It is applied as a final solution when all other control actions fail to maintain the security and reliability of power system. In the past, a lot of research has been conducted on UFLS scheme mainly for transmission system. However, few papers have discussed the UFLS implementation in islanded distribution network connected with DG. The aim of this chapter is to present literature review of UFLS schemes applied on islanded distribution network connected with DG.

3.1 Importance of Frequency Balance and Control

Practically, power system frequency is never in a balance state, since, the load demand varies continuously. Due to this, system frequency always increases or decreases. The system frequency decreases if load exceeds and increases when power generation is greater than load demand. However, constant power system frequency is required due to following reasons (Mahat, et al., 2010):

(a) In a distribution system, most of the electric motors are required to operate at constant speed. The motor speed is directly proportional to system frequency. Hence, any change in system frequency will result in motor speed variation.

- (b) Some electronic application such as inverter and converter uses the main frequency as a basis for timing the various processes. Since, they use this frequency for time calculation.
- (c) Transformers operation is very sensitive to frequency and voltage variation.
- (d) The most important part of a generator is its auxiliary part. Generator output depends directly upon the performance of this auxiliary part. If frequency is low, speed will decrease which results to underperformance of these auxiliary equipments. This will result in reduced output power. Hence, constant frequency is required for stable power system operation.

Power system frequency is directly proportional to generator speed. Hence, frequency can be controlled by controlling generator speed. Normally, prime mover of generator is equipped with governor for sensing the speed continuously and modifies prime mover supply for controlling constant speed. When load is suddenly increased, extra energy demand is initially supplied by rotational inertia of generator. Due to this, rotational speed of generator is decreased, which results to proportional decrease in system frequency. Governor opens the turbine gate in order to increase water flow into turbine. Increase in water flow will also increase turbine speed. This increased turbine speed will result in increasing system frequency and thus, frequency recovered in an acceptable range.

3.2 Power System Swing Equation

Power swing equation provides the relationship between torque deviation and variation in angular acceleration (Hadi, 1999) and (Kundur, 1994). It is used to estimate the power imbalance during load variation. Turbine produces mechanical power which is supplied to

generator shaft. Generator converts mechanical power into electrical power. Mechanical torque T_{mech} is produced at turbine from water flow and electrical torque T_{elec} is produced as a result of load connection. Any difference between them can cause fluctuation on generators speed, resulting in speed variation. This speed variation will further result to the variation of system frequency ("IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration," 2007). This relationship is given in Equation (3.1):

$$T_{mech} - T_{elec} = J \frac{\partial \omega}{\partial t} \quad (3.1)$$

In Equation (3.1), ω is an angular velocity; J is moment of inertia of generator and turbine. When angular velocity in radian per second ω_m is multiplied with this Equation, then T_{mech} and T_{elec} will become mechanical power P_{mech} and electrical power P_{elec} as given:

$$P_{mech} = \omega_m \times T_{mech}, \quad P_{elec} = \omega_m \times T_{elec}$$

$$P_{mech} - P_{elec} = J \times \omega_m \times \frac{\partial \omega}{\partial t} \quad (3.2)$$

Equation (3.2) clearly shows that system frequency depends upon P_{mech} and P_{elec} variation. This Equation can be normalized in term of per unit inertia constant H , that defines as kinetic energy. The inertia constant H is defined in Equation (3.3)

$$H = \frac{1}{2} \times \frac{J \times \omega_m^2}{S_{base}} \quad (3.3)$$

If P is the number of poles in synchronous machine, mechanical speed is related to electrical speed by Equation (3.4)

$$\omega = \frac{P}{2} \times \omega_m \quad (3.4)$$

Whereas, ω_m does not change during steady state, H can be evaluated by the synchronous speed. After substituting (3.3) and (3.4) into Equation (3.2), the Equation becomes:

$$\frac{2H}{\omega} \times S_{base} \times \frac{\partial \omega}{\partial t} = P_{mech} - P_{elec} \quad (3.5)$$

Dividing Equation (3.5) by S_{base}

$$\frac{2H}{\omega} \times \frac{\partial \omega}{\partial t} = \frac{P_{mech}}{S_{base}} - \frac{P_{elec}}{S_{base}} \quad (3.6)$$

Now, powers in Equation (3.6) can appear in per unit

$$P_{m(p.u)} - P_{e(p.u)} = \frac{2H}{\omega} \times \frac{\partial \omega}{\partial t} \quad (3.7)$$

where $P_e (p.u)$ and $P_m (p.u)$ are electrical and mechanical power expressed in per unit respectively, and H is inertia constant in per unit. Equation (3.7) represents the equation of motion for a synchronous machine. It is commonly referred to as the swing equation, because it represents swing in rotor angle during disturbance.

3.3 Abnormal Frequency and Voltage in Power System

Power swing equation provides the amount of frequency fluctuation, when there is mismatch between generation and load demand in the system. It means that when load demand exceeds the generation, system frequency will decline. Frequency drop will depend upon the governor response and spinning reserve that will help to recover frequency to

desired value. However, if frequency declines very fast and come out of ideal range, then under frequency load shedding technique must be applied in order to recover the system frequency. The frequency will become stable at some new value, if power imbalance is greater than spinning reserve of system. In this situation, under frequency load shedding is necessary to avoid frequency to stable at new value lower than the acceptable limit.

The co-ordination of under frequency protection of generator with under frequency load shedding scheme is very important. If system frequency goes below a threshold value, under frequency protection relay of generator will operate and system will collapse unnecessarily. Hence, under frequency load shedding technique should be applied in such a way that frequency recovers without going below the threshold value. For a power system operating within 50 Hz frequency, the minimum allowable operating frequency usually specified by the manufacturer according to the turbine type is 47.5 Hz (Lukic, et al., 1998).

Power plant auxiliary services are more demanding than generators in terms of minimum allowable frequency. In fact, they begin to malfunction at a frequency of 47.5 Hz, while the situation becomes critical at about 44-46 Hz. In this case, there is a cascade effect in which the asynchronous motors of the auxiliary services are disconnected from the protection zones. Turbine natural frequencies are kept by designing far from the nominal speed, so that they are not likely to operate in a situation of resonance, which could destroy the turbine or cause a reduction of its life. In fact, every commercial turbine can sustain up to 10 contingencies at 47.5 Hz for one second without being jeopardized or hazard ("IEEE Guide for Abnormal Frequency Protection for Power Generating Plants," 1987). Moreover, in order to obtain a larger degree of security and according to common practice, the minimum allowable frequency technical limit is 47.5 Hz and the generator is not allowed to operate below this frequency (Delfino, et al., 2001). Similarly, there is a limit of abnormal

voltages in a system. According to IEEE standard, if abnormal voltages lying between 0.5p.u and 0.88p.u range, the system voltage should recover within 2 s in order to ensure system security ("IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems," 2003).

3.4 Load Shedding Scheme and its Types

Power plants should produce adequate generation for meeting the load requirements. However, due to economic and security reason, there is limitation on the excess capacity of generation. When load exceeded the generation, the only option to get rid from over load is to shed the extra load. Hence, load shedding is one of protective option that can be applied to power system for preventing the loss of generators; equipments damage and finally prevent blackouts to the power system. There are two types of load shedding schemes:

- Under frequency load shedding scheme (UFLS)
- Under voltage load shedding scheme (UVLS)
- **Under Frequency Load Shedding Scheme (UFLS):** According to IEEE standard under frequency load shedding scheme is defined as “*Under frequency load shedding must be performed quickly to arrest power system frequency decline by decreasing power system load to match available generating capacity.*” ("IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration," 2007).
- **Under Voltage Load Shedding Scheme (UVLS):** Under voltage load shedding scheme is applied to prevent voltage collapse in the system.

The load shedding scheme should be capable of shedding adequate load for the restoration of system frequency to acceptable range. This research will discuss and focus on under frequency load shedding schemes.

3.4.1 Under Frequency Load Shedding Techniques

UFLS scheme is applied as the last resort when all available controls fail to maintain the system frequency within acceptable range. However, before applying the UFLS scheme, some important factors should be considered for maintaining system stability (Delfino, et al., 2001).

- Minimum acceptable frequency should be defined for secure system operation.
- Maximum overload should be predicted.
- Value of load to be shed.
- Different frequency thresholds.
- Number and size of steps for load shedding and load priority should be fixed

The minimum acceptable frequency is dependent on the system equipment such as generator type and its auxiliary device, such as steam turbine. Steam turbine is more sensitive to frequency drop. UFLS protection for generators is implemented based on turbine and generator design and type. Load shedding scheme should also fulfil the following main tasks (Delfino, et al., 2001).

- The action should be quick, so that frequency dropped can be stopped before system reach to a position which leads to equipment damage.

- Protection system should be reliable and must avoid repetitive mistakes. The malfunctionality should be strictly avoided, as it will lead to failure to most part of the system.
- For restoring the grid security, minimum load should be disconnected so that lowest allowable frequency overshoot can be avoided

Generally, load shedding schemes can be divided into three main categories

- Conventional load shedding techniques
- Adaptive load shedding techniques
- Intelligent load shedding techniques

3.4.1.1 Conventional Load Shedding Techniques

Under frequency load shedding through frequency relay is the most common type of conventional load shedding technique. In this technique, under frequency relays will operate when system frequency falls below a certain threshold, and shed some amount of electrical power in step wise manner (Delfino, et al., 2001). This technique is widely applied in transmission system such as in Tenaga Nasional Berhad's (TNB) utility of Malaysia. In order to use this technique, UFLS relays have been installed to disconnect the load with respect to falling frequency in the event of a major loss of generation. The scheme is designed to disconnect the load at predefined frequency stages so as to match the losses in generation. However, in order to minimize over shedding, it is always better to have more stages with smaller load at each stage. Moreover, tripping a big block of load at one time will lead to a large impact to an already weakened system. Previously 4-stage and

6-stages scheme were implemented. However 11 stage scheme and 15 stage scheme has also been designed in order to prevent UFLS scheme from over shedding of loads (Mohd Zin, et al., 2004).

3.4.1.2 Adaptive Load Shedding Techniques

The improved conventional load shedding scheme is known as adaptive load shedding scheme. In adaptive load shedding scheme, rate of change of system frequency is measured and when frequency falls to certain threshold, magnitude of disturbance is estimated by using power swing equation. As the rate of change of frequency (ROCOF) magnitude is proportional to system inertia constant and to size of disturbance as described previously in Equation (3.7). By measuring frequency and its ROCOF from Equation (3.7) and inertia constant, the value of power imbalance can be estimated. In adaptive load shedding scheme following points should be considered:

- Magnitude of disturbance estimated.
- Disturbance localization.
- Distribution of control action throughout the power system.

3.4.1.3 Intelligent Load Shedding Techniques

An effective load shedding scheme requires complete knowledge of power system dynamics and process restrictions. Intelligent load shedding applies real time data acquisition that continuously updates a real time system model. The advantages of intelligent load shedding scheme is that it determines most efficient solution for system

protection by shedding only necessary amount of load. In short, an intelligent load shedding scheme have better response in terms of time, precise anticipate frequency fall and make a fast, optimum and reliable load shedding decision. The data for intelligent load shedding scheme which is required before and after the disturbance is summarized below (Shokoo, et al., 2005):

- Total load demand and consumption of system.
- Total system power generation.
- Spinning reserve of each generating unit.
- System configurations.

3.4.2 Response Based and Event Based Methods

Another definition of load shedding scheme applied on distribution network has been defined in terms of response based and event based methods. Both are defined separately as below (Seyedi & Sanaye-Pasand, 2009).

- **Response Based System Protection:** In this scheme of load shedding, response of power system against different disturbances is applied as source for power system protection. Input signals for this case may be frequency or voltage.
- **Event Based System Protection:** In this method, specific elements in power system such as transmission line or generators are shed based on decision. This method

involves a communication link to transmit state of important elements to control centre and under frequency relays.

3.5 Load Shedding Techniques in Transmission Network

Transmission system normally employs conventional load shedding scheme which consists of under frequency relay for eliminating the over load effects (Jones & Kirkland, 1988). Load shedding technique is based on frequency decline. When system frequency falls below certain acceptable range, following steps are carried out:

- (a) First load shedding steps are specified.
- (b) Time delay is selected for recovery of system frequency.
- (c) When any step is activated but frequency continues to fall then next steps will be also activated.

In comparison to the conventional load shedding scheme, another technique is the adaptive load shedding scheme. This technique employ rate of change of frequency to estimate the magnitude of load disturbance. In 1994, adaptive load shedding scheme was applied by measuring ROCOF, system inertia, system damping measurement from SCADA system (Thompson & Fox, 1994). The load shedding amount was calculated by control centre. Another adaptive load shedding scheme designed for protection of dynamic instability and frequency collapse is presented in (Terzija & Koglin, 2002). In this scheme, load disturbance is estimated through power swing equation.

A comparative centralized adaptive load shedding scheme consisting of response based and combination of event and response based is applied in (Pasand & Seyedi, 2007). In this

scheme, response based method is based on adaptive load shedding and uses power swing equation as given in Equation (3.7) for determining the power imbalance in system.

The second algorithm is based on event based technique. In event based technique, when generator tripped, a signal is sent to the control centre for informing that this generator is tripped and how much generation is lost from the system. After that, required amount of load needed to be shed is calculated.

An intelligent adaptive load shedding technique is proposed by (Vijay Vittal, 2002). This technique combines the conventional and adaptive load shedding scheme. First, relays operate as conventional load shedding mode having longer time delay and smaller frequency thresholds. The second layer applies frequency decline rate for the estimation of load disturbance magnitude. This layer operates when large power system encountered a large disturbance.

3.6 Load Shedding Techniques in Distribution Network

Mostly, under frequency load shedding schemes have been applied in transmission network. Only a few papers have applied under frequency load shedding scheme in distribution network. Hirodonis, et al. proposed adaptive load shedding scheme for UK distribution network (33KV) comprised of different type and size of load as well as DGs. This research mainly considers estimation of disturbance magnitude, location of disconnection and control action to be taken by individual relays. The scheme estimates power disturbance by using power swing equation. The power disturbance value is sent to load shedding scheme for tripping the loads according to their magnitude and priority. This

technique is totally different from conventional scheme and can provide the optimal load shedding in distribution network (Hirodantis, et al., 2009),

Ding, et al. had applied a new load shedding scheme for Navy shipboard power system. The navy shipboard power system is an islanded power system and consists of 10 Buses having DC and AC voltage of 800V and 450V respectively. Proposed load shedding scheme perform action after taking input from load prioritizing module (Ding, et al., 2006).

Another load shedding scheme based on frequency information, ROCOF, customers' willingness to pay and load history was proposed in (Mahat, et al., 2010). The test system consists of one combined heat power plant and three wind turbine generators supplying 11 loads. This scheme creates load look-up table based on load history and customer willingness to pay. The load which is not willing to pay by customer is ranked first and loads are ranked last who are most willing to pay by customers. With the following parameters, this scheme provides optimum load shedding scheme in distribution network.

CHAPTER 4

RESEARCH METHODOLOGY

Commonly, mechanical hydraulic governor and electro-hydraulic PID governor are used for load frequency control of mini hydro power plants. However, mechanical hydraulic governor may fail to provide robust control due to their slow response, and electro-hydraulic PID governor have the problem in obtaining correct parameter tuning. To address this problem, fuzzy logic control technique can be applied. The Proposed load frequency control (LFC) scheme applies fuzzy logic control as governor. This research will compare proposed fuzzy based governor with PID based governor to show its superiority.

Apart from this, during islanding operation, system frequency and voltage of these plants are severely disturbed. This large frequency variation may lead to power collapse, if not recovered quickly and properly. To avoid this, under frequency load shedding scheme is performed to shed some load in order to keep system running, though at reduced capacity. This research proposed an adaptive and intelligent under frequency load shedding (UFLS) scheme based on fuzzy logic control for shedding the loads. The Proposed UFLS scheme consists of fuzzy logic load shedding controller (FLLSC) for estimating the power imbalance, and load shedding controller module (LSCM) for shedding the respective loads. To observe the governor response on proposed UFLS scheme, both PID and fuzzy based governor are employed in the test system. Each UFLS case is tested with PID governor as well as with fuzzy based governor.

This chapter deals with modelling of proposed scheme for LFC and UFLS scheme. LFC scheme requires designing of a fuzzy based governor, PID governor, and mini-hydro components. Whereas, UFLS scheme requires modelling of similar components as needed for LFC technique, except designing of fuzzy logic load shedding controller (FLLSC) and load shedding controller module (LSCM). The overview of proposed UFLS scheme is explained as in the following section.

4.1 Overview of Proposed Load Shedding Scheme

This research proposed a fuzzy based under frequency load shedding strategy to shed optimum loads in an islanding mode to stabilize the system frequency. Proposed UFLS strategy is based on frequency and df/dt information. Fuzzy logic load shedding controller (FLLSC) uses these values as input, and intelligently determines type of load disturbance whether Event or Response based and estimates the power imbalance during these disturbances. FLLSC sends this value to load shed controller module (LSCM) for shedding loads according to load priority. Combination of event based and response based method are used for applying load shedding scheme in the network. Standard frequency pick value to begin load shedding scheme is set to 49.5Hz as practised in TNB, Malaysia (Mohd Zin, et al.). FLLSC estimates the value of fall in frequency and disturbance magnitude. If frequency value is less than 49.5Hz, load shedding strategy will start to operate to shed optimum load in order to stabilize frequency. Figure 4.1 illustrates the overview of load shedding scheme for an islanded distribution network connected with mini-hydro type DG.

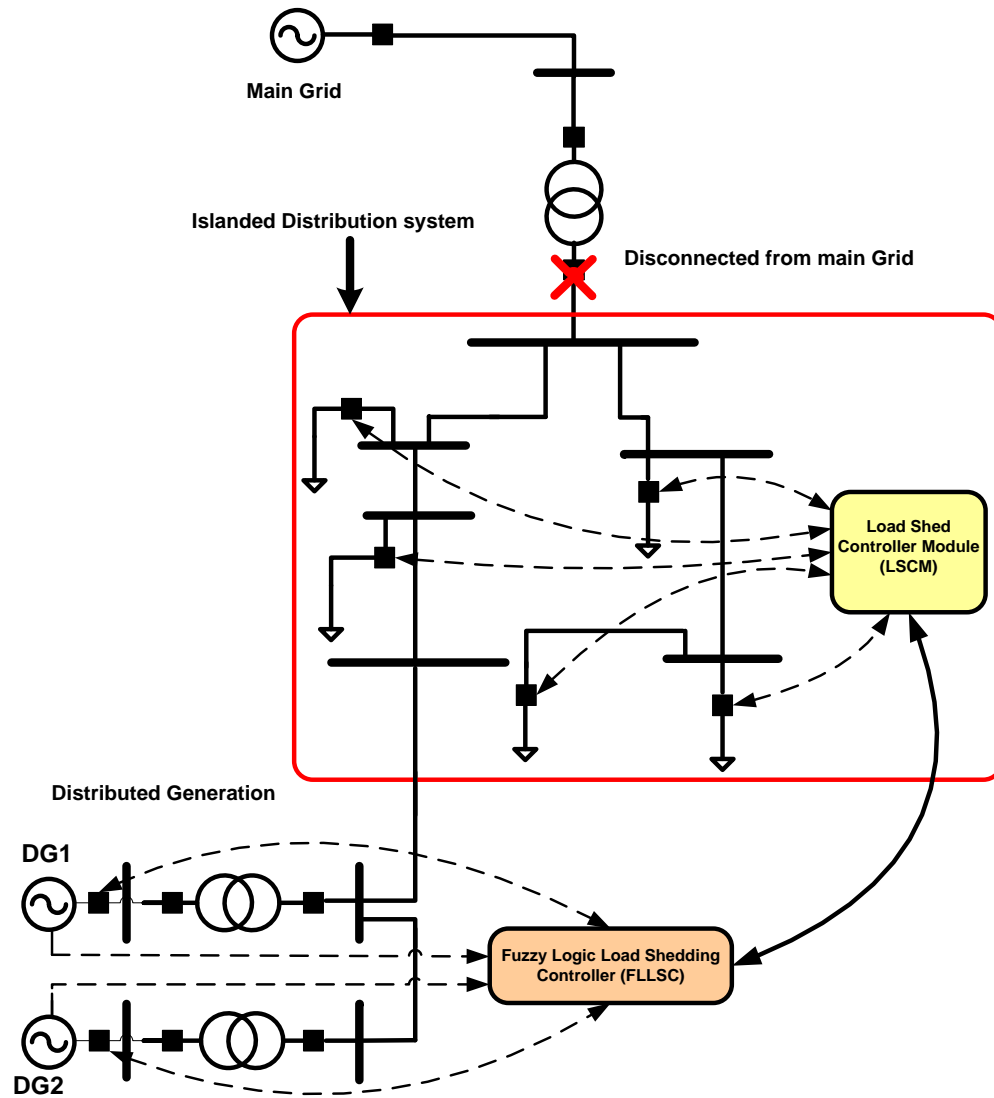


Figure 4.1 Proposed load shedding scheme layout

4.2 Methodology for Proposed UFLS Scheme

The Proposed UFLS scheme uses fuzzy logic approach for islanded system. Proposed UFLS scheme is based on system frequency, df/dt and load prioritization. The scheme consists of two main modules and flow chart of proposed scheme is shown in Figure 4.2.

- (a) Fuzzy logic load shedding controller (FLLSC)
- (b) Load shed controller module (LSCM).

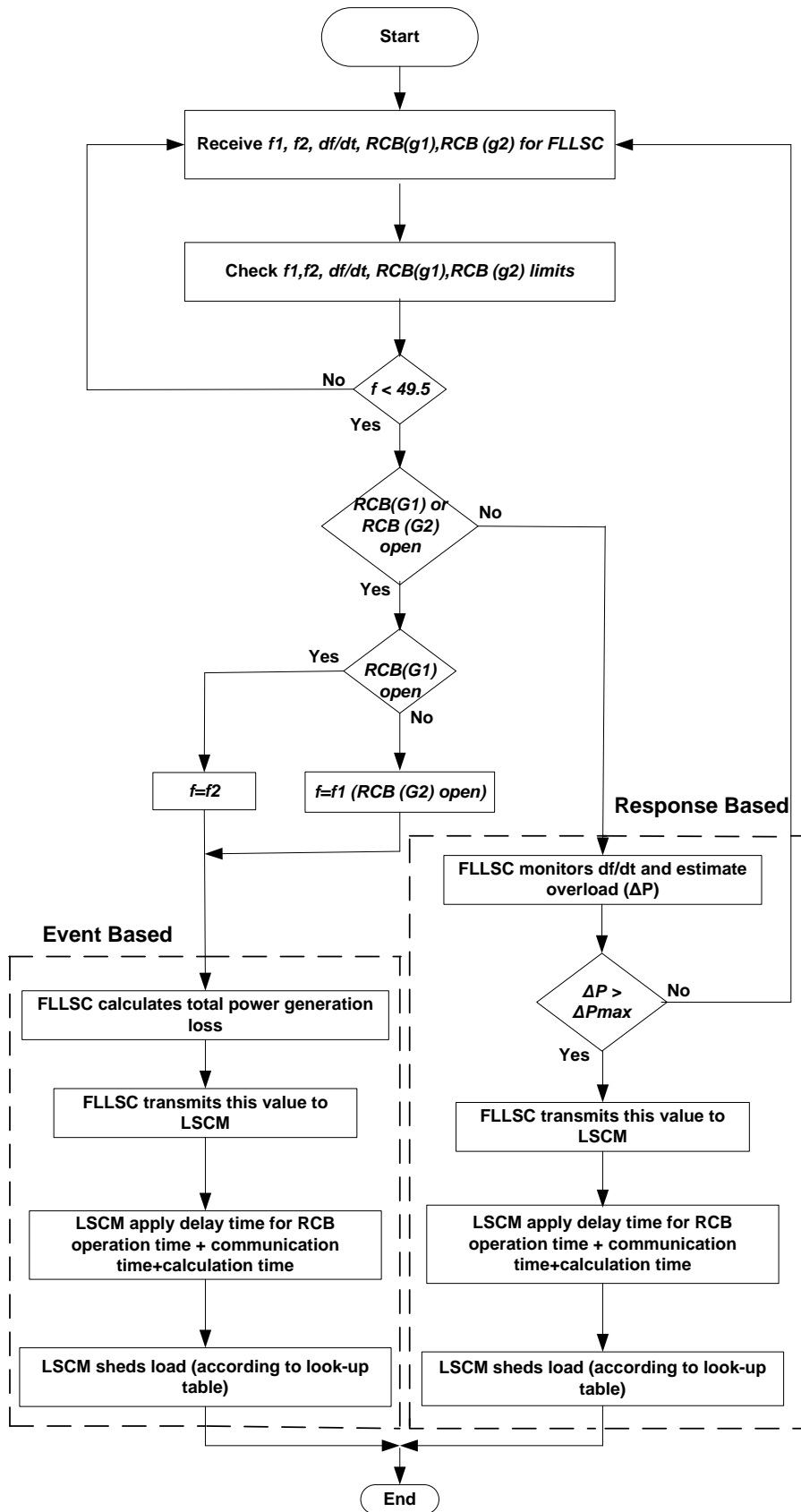


Figure 4.2 Flow chart of proposed load shedding scheme

FLLSC continuously monitors DG frequency and is responsible for determining system state at every instant of time. DG in this case consists of two mini hydro power plant (MHPP) units with frequency f_1 and f_2 respectively. FLLSC checks whether any of DG unit is disconnected from the network. If this happen, network frequency will follow the frequency of DG unit that is still in operation. If both DG units are still in operation, average frequency (f) of both DG units is taken.

When a load disturbance (event based or response based) occurs in the system, FLLSC monitors system frequency whether it drop to certain value, in this case 49.5 Hz. If this happens, FLLSC determines its state and estimates amount of load to be shed. If estimated amount ΔP is greater than ΔP_{max} ($\Delta P_{max} = 50\text{KW}$, minimum load value in distribution network), FLLSC sends estimated ΔP to LSCM for shedding respective loads to stabilize the frequency. The loads are classified into three categories; vital, semi-vital and non-vital. The non-vital, semi-vital and vital loads represents residential, industrial factory and medical hospital loads respectively. Non-vital loads have the lowest priority and will be shed first followed by semi-vital and vital loads. FLLSC sends estimated value to LSCM via communication link. The delay time which includes calculation time, communication time and circuit breaker operation time is assumed as 100 ms, which is according to practical considerations (Anderson & Mirheydar, 1992; "IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems," 2003).

Real time measurement and Remote Circuit Breaker (RCB) are facilitated at each of the load feeder. The system state variable measurement (i.e. active power, frequency and voltage) are monitored by FLLSC whereas breakers status are monitored by LSCM. In this study, distribution network is assumed to have reliable monitoring devices and fast communication system for transmitting data.

In FLLSC, there are two strategies; (1) Event based and (2) Response based scheme. FLLSC decides right strategies based on frequency, df/dt and breaker status at the DG units. The description of these strategies is as follows:

4.2.1 FLLSC for Event Based Case

Event based case may occur when one of the DG unit is tripped during islanded mode. This tripping incident may be initiated by the failure operation or malfunction of generator differential protection. It may also happen due to transmission line failure in power system. The Proposed FLLSC will intelligently estimate the amount of load to be shed. thus, preventing system from blackouts. When Event based occurs, FLLSC will estimate total power imbalance between generation and load demand given in Equation (4.1):

$$\Delta P = P_{DG} - P_{Load} \quad (4.1)$$

where,

ΔP is power imbalance,

P_{DG} is DG rated power,

P_{Load} is total load demand.

FLLSC sends ΔP value to LSCM which sheds the optimum load according to load priority defined in load look-up table.

4.2.2 FLLSC for Response Based Case

Response based case occur due to sudden increment of load in an islanded system. In this case, number of load to be shed depends on the disturbance magnitude. FLLSC

estimates the power imbalance by using frequency and df/dt as input signals. After estimating power imbalance, FLLSC sends signal to LSCM to shed the required load.

4.3 Modelling of Fuzzy Based Governor in PSCAD

Fuzzy logic controller can be applied in PSCAD either by using fuzzy logic controller built in Matlab or writing C-program for fuzzy logic in PSCAD itself. The later method which is applied in this study has an advantage that the system presents all simulation aspects within a single integrated environment. Hence, simulation time is fast. The proposed fuzzy logic based governor has two inputs (frequency error and load) and one output (turbine gate). Fuzzy logic based governor receives frequency error and load as input signal, and generates output signals to servomotor for opening or closing the turbine gate. Fuzzy logic based governor comprises of fuzzification, rule base, inference mechanism and defuzzification steps as shown in Figure 4.3.

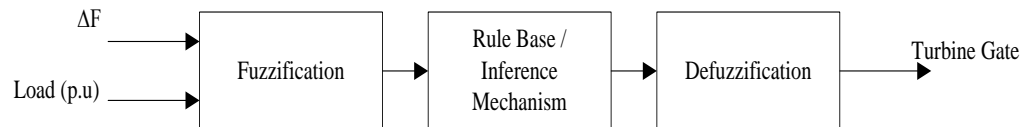


Figure 4.3 Block diagram of proposed fuzzy based governor

The linguistic variables membership functions of input frequency error are MN (more negative), N (Negative), Z (Zero), P (Positive), MP (more positive) and input load membership functions are VUload (very under load), Uload (under load), Nload (normal load), Hload (heavy load), VHload (very heavy load). The linguistic variables of output

turbine gate are Fclose (full close), Hclose (half close), Qclose (quarter close), Nopen (normal open), Qopen (quarter open), Hopen (half open), Fopen (full open).

In fuzzification, real input values are converted into fuzzy set values, which assign degree to which these inputs belong to each of the appropriate fuzzy sets. Fuzzification is carried out through equation of slope. A snapshot for determining membership degree of MN (more negative) member ship function of frequency error input is shown in Figure 4.4 and explained by Equations (4.2)-(4.5).

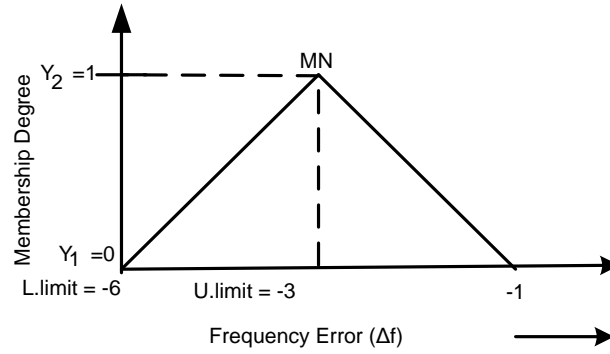


Figure 4.4 Snapshot of frequency error fuzzification at certain time instant

$$\text{Equation of slope} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{y - y_1}{x - x_1} \quad (4.2)$$

$$\text{slope} = m = \frac{y_2 - y_1}{x_2 - x_1} \quad (4.3)$$

$$\frac{y_2 - y_1}{U_{limit} - L_{limit}} = \frac{m.degree - y_1}{\Delta f - L_{limit}} \quad (4.4)$$

$$m.degree = \text{slope} \times (\Delta f - L_{limit}) + y_1 \quad (4.5)$$

All the membership functions of the proposed fuzzy based governor consist of triangular membership functions as they provide smooth control and are shown in Figure 4.5-4.7.

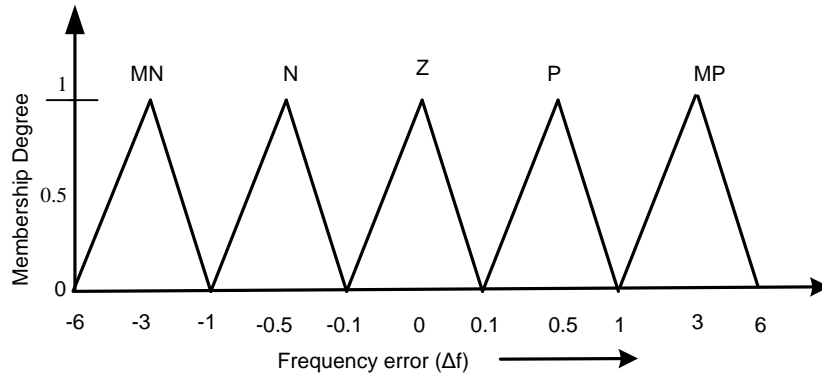


Figure 4.5 Frequency error membership functions

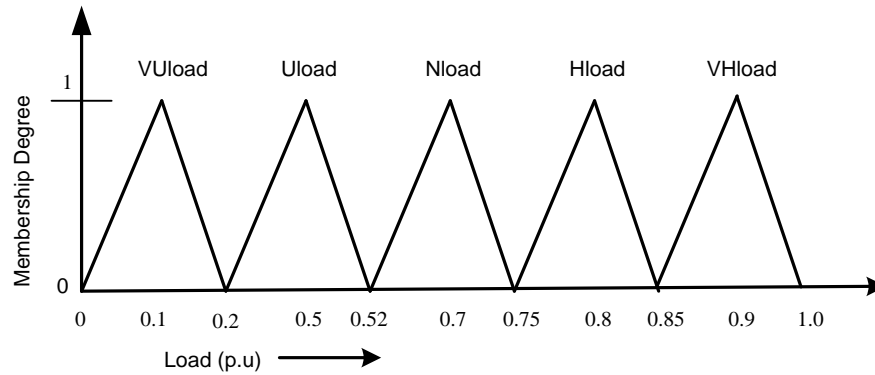


Figure 4.6 Load membership functions

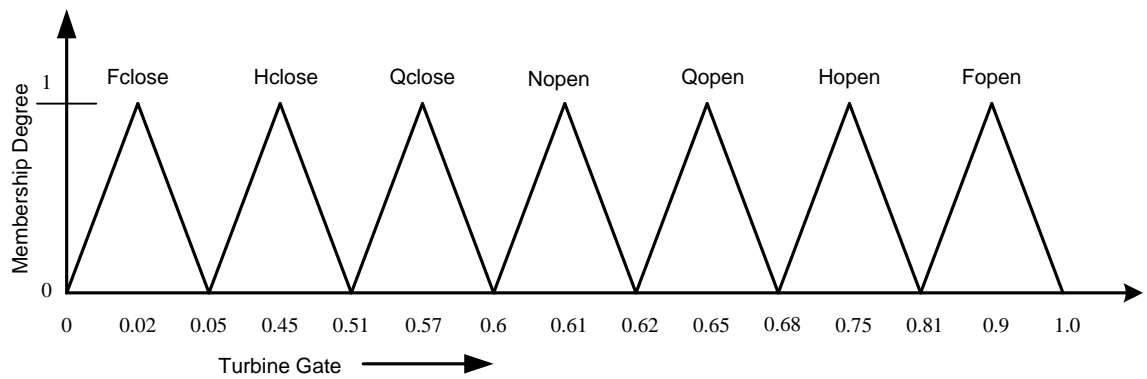


Figure 4.7 Turbine gate membership functions

Fuzzy based governor input and output membership functions are modelled using C-program by using one dimensional array concept. The triangular membership functions are divided into two slope equations for fuzzification. One dimensional array in C-program for Figure 4.4 is given as:

```
float MN[3]={-6.0,-3.0,-1.0};
```

For vertical axis another one dimensional array is employed representing the corresponding values of membership function along vertical axis:

```
float vert[3]={0,1,0}
```

where *vert* represents vertical axis and values 0, 1 and 0 are corresponding values of -6, -3 and -1 along vertical axis as shown in Figure 4.4. A sample program for fuzzification of one part of membership function from -6 to -3 is given as below:

```
if ( freq error >= MN[0] && freq error <= MN[1])
{
    x1=MN[0];
    y1=vert[0];
    x2=MN[1];
    y2=vert[1];
    slope = (y2-y1) / (x2-x1);
    m.degree = slope × (freq error-x1) + y1;
}
```

All other input and output membership functions of fuzzy logic based governor are fuzzified by using the same one dimensional array concept. Fuzzy rule base is applied in IF-THEN rule form to assign the input and output control such as:

IF frequency error is negative and load is low THEN close turbine gate.

IF frequency error is positive and load is high THEN open turbine gate.

The other rules of fuzzy based governor are summarized in Table 4.1.

Table 4.1 Rule table for fuzzy based governor

		Frequency error				
		MN	N	Z	P	MP
Load (p.u)	VUload	Fclose	Hclose	Nopen	Nopen	Nopen
	Uload	Hclose	Qclose	Nopen	Nopen	Nopen
	Nload	Qclose	Qclose	Nopen	Qopen	Qopen
	Hload	Nopen	Nopen	Nopen	Qopen	Hopen
	VHload	Nopen	Nopen	Nopen	Hopen	Fopen

Inference mechanism evaluates active signals for taking control actions from the fuzzy rules. Finally, defuzzification is carried out through weighted average to convert the fuzzy linguistic variable into real crisp values. Defuzzification through weighted average is determined as:

$$weighted\ average = \frac{\sum_{i=1}^n m_i \times w_i}{\sum_{i=1}^n m_i} \quad (4.6)$$

where,

m_i is membership degree of each output rule,

w_i is weight associated with each rule,

n is number of active rules.

The advantage of this method is that it is computationally fast, easier and provides accurate results.

4.4 Fuzzy logic Load Shedding Controller (FLLSC) Model in PSCAD

Fuzzy logic load shedding controller (FLLSC) plays an important role in proposed UFLS scheme. The major part of UFLS depends upon FLLSC, which determine system state and estimates optimum amount of load to be shed. FLLSC modelling is based on power swing equation for estimating the power imbalance and is given in Equation (4.7):

$$\frac{2 \times H}{f} \times \frac{\partial f}{\partial t} = \Delta P \quad (4.7)$$

Where,

H is Inertia constant of generator,

f is system frequency,

$\frac{\partial f}{\partial t}$ is rate of change of frequency,

ΔP is power imbalance.

From Equation (4.7), It is clear that amount of power imbalance depends upon Inertia constant of generator (H), frequency and rate of change of frequency.

Fuzzy logic load shedding controller for this case consists of two inputs and one output. The inputs of fuzzy logic load shedding controller are frequency (f) and rate of change of frequency (df/dt) and output is amount of load shed (L_{shed}). Depending upon input values, fuzzy logic will calculate the amount of load required to be shed. FLLSC

continuously check, whether distribution network has encountered Event based or Response based load disturbance. This is done by checking the breaker status of generating unit, frequency and rate of change of frequency (df/dt). The output of fuzzy logic load shedding controller is sent to LSCM for shedding the required load. The block diagram of fuzzy logic load shedding controller (FLLSC) is shown in Figure 4.8.

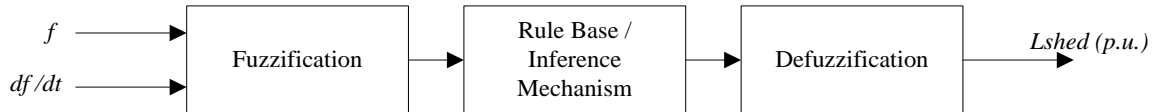


Figure 4.8 Block diagram of fuzzy logic load shedding controller

Fuzzy logic load shedding controller (FLLSC) is designed in PSCAD by writing C-program for fuzzy logic in PSCAD itself. FLLSC modelling is carried out in similar manner as discussed for fuzzy based governor modelling in the previous section. The linguistic variables of membership functions of input frequency are Low (Low), Vlow (Very Low), EXtlow (Extremely Low), VEXtlow (Very Extremely Low) and input rate of change of frequency (df/dt) membership functions are HN (High Negative), LN (Low Negative), LP (Low Positive), HP (High Positive). The linguistic variables of output Lshed are Vsshed (Very Small Shed), Sshed (Small Shed), Bshed (Big Shed), Vbshed (Very Big Shed). The respective membership function of Frequency, (df/dt) and Lshed are shown in Figure 4.9-4.11. The rule table for FLLSC is shown in Table 4.2.

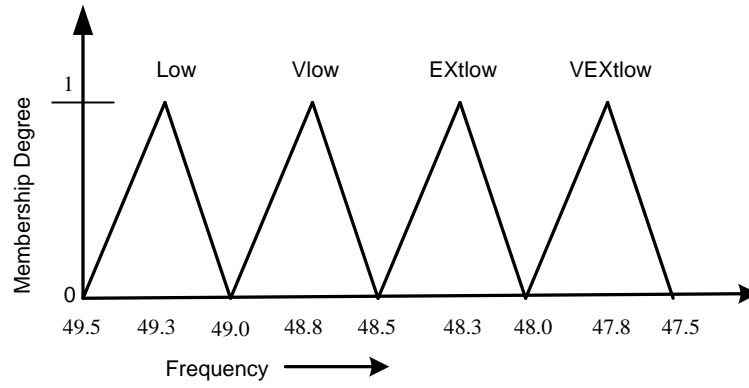


Figure 4.9 Frequency membership functions

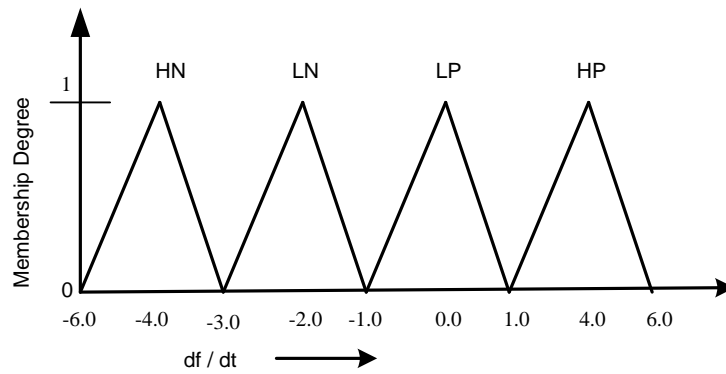


Figure 4.10 Rate of change of frequency (df/dt) membership functions

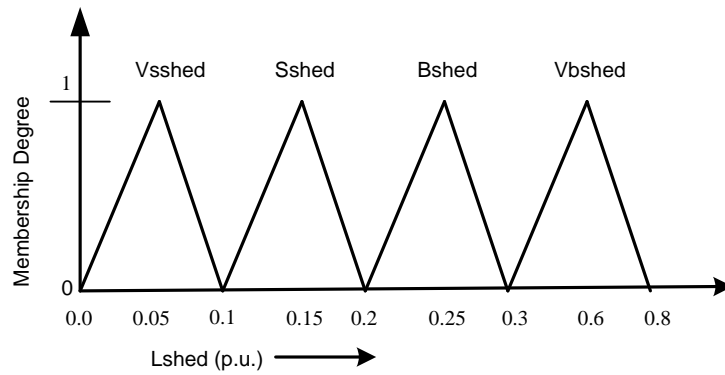


Figure 4.11 Lshed (p.u.) membership functions

Table 4.2 Rule table for fuzzy logic load shedding controller (FLLSC)

		Frequency			
		Low	Vlow	Extlow	Vextlow
(df / dt)	HN	Sshed	Bshed	Bshed	Vbshed
	LN	Sshed	Sshed	Bshed	Vbshed
	LP	Vsshed	Vsshed	Ssshed	Sshed
	HP	Vsshed	Vsshed	Vsshed	Vsshed

Fuzzy logic load shedding controller with LSCM module designed in PSCAD is shown in Figure 4.12.

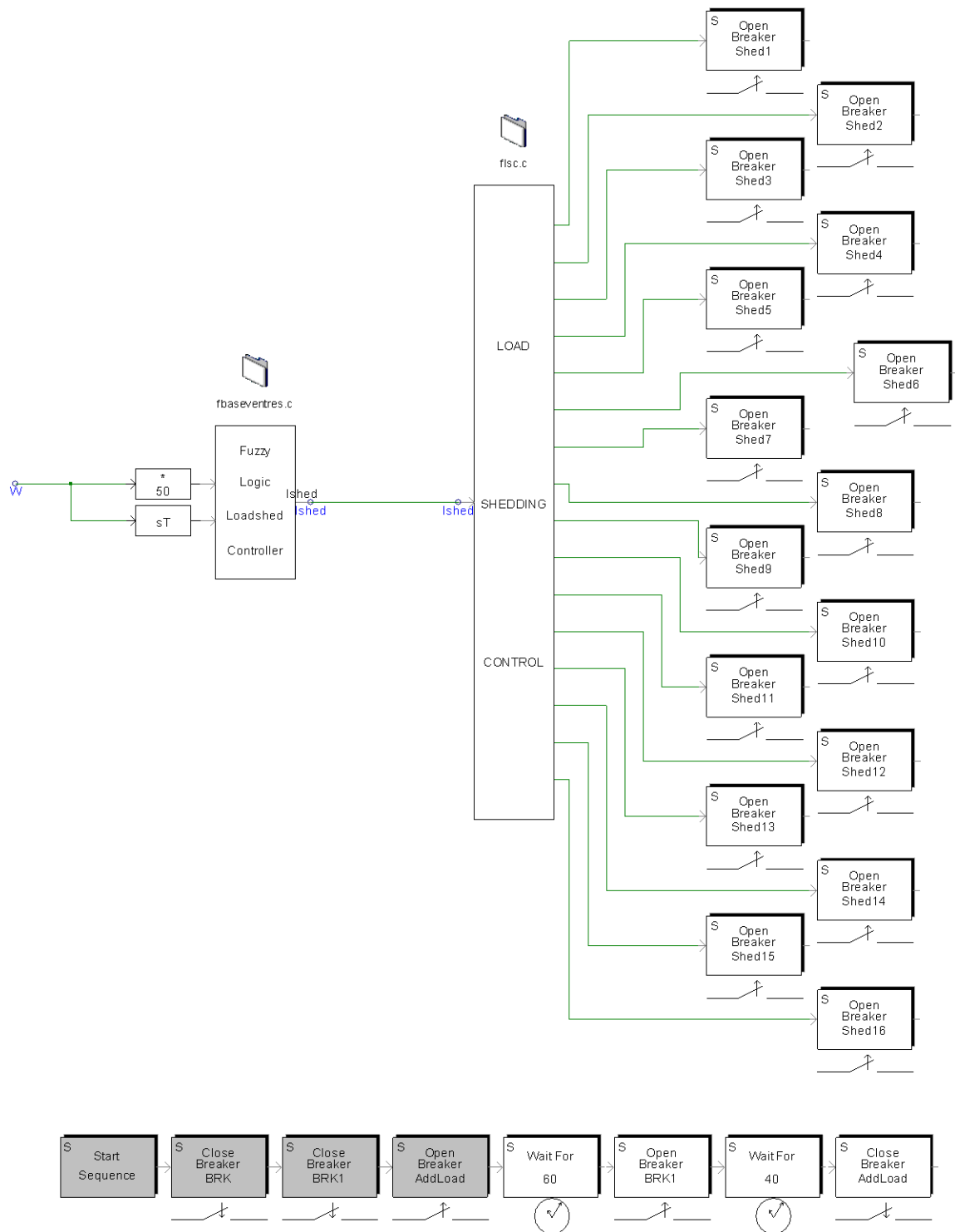


Figure 4.12 Fuzzy logic load shedding controller with LSCM module

4.5 Exciter System Model

The basic function of excitation system is to provide direct current to the synchronous machine field winding. In addition, excitation system also performs control functions essential to the satisfactory performance of power system. Control function includes the control of voltage and reactive power flow. Excitation system provides supply and automatically adjusts field current of synchronous generator to maintain the terminal voltage. The excitation system can be classified into three main categories:

- DC excitation system models
- AC excitation system models
- Static excitation system models

The excitation system model chosen in this research is based on IEEE type AC1A standard model. It is shown in Figure 4.13.

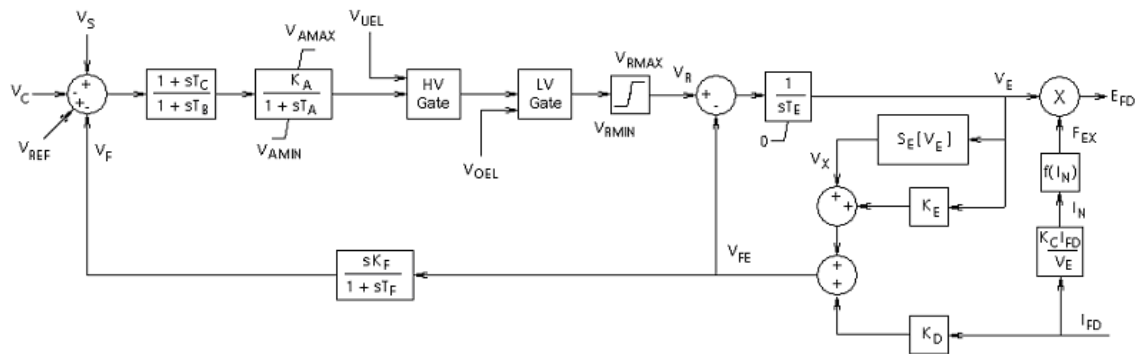


Figure 4.13 Transfer function of IEEE type AC1A excitation system model

This model provides a field-controlled alternator excitation system with un-controlled rectifiers, and is applicable to brushless excitation systems (Kundur, 1994). The exciter

does not employ self-excitation, and voltage regulator power is taken from a source that is not affected by external transients. For large power system stability studies, the exciter alternator synchronous machine can be represented by the simplified model as shown in Figure 4.13 ("IEEE Recommended Practice for Excitation System Models for Power System Stability Studies," 2006). Typical parameters used in the simulation are presented in Table 4.3.

Table 4.3 Sample data of IEEE AC1A excitation model parameters

Parameter	Value	Parameter	Value
T_C	0	K_F	0.03
T_B	0	T_F	1
K_A	400	T_E	0.8
T_A	0.02	K_E	1
V_{AMAX}	14.5	K_C	0.2
V_{AMIN}	-14.5	K_D	0.38
V_{RMAX}	6.03	V_{RMIN}	-5.43
$SE(VE1)$	0.1	$SE(VE2)$	0.03
$VE1$	4.18	$VE2$	3.14

4.6 Hydraulic Turbine and Governor Model

The main purpose of governor is to regulate generator speed in order to keep frequency at constant value. Governor senses speed variation and control the turbine gate for water

flow. A governor and turbine determines the mechanical torque and power applied to generator. The general block diagram consisting of hydraulic turbine and governor is shown in Figure 4.14.

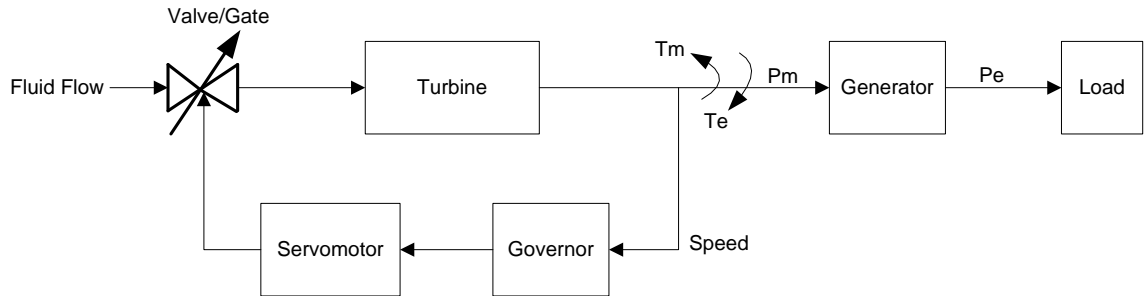


Figure 4.14 Block diagram of turbine speed control with governor

This research employs two governors for speed control one electro-hydraulic PID governor and the proposed fuzzy based governor. The aim of using two governors is to compare their response at different load variations. Fuzzy based governor modelling is already explained in Section. 4.2. Block diagram of electro-hydraulic PID governor is shown in Figure 4.15.

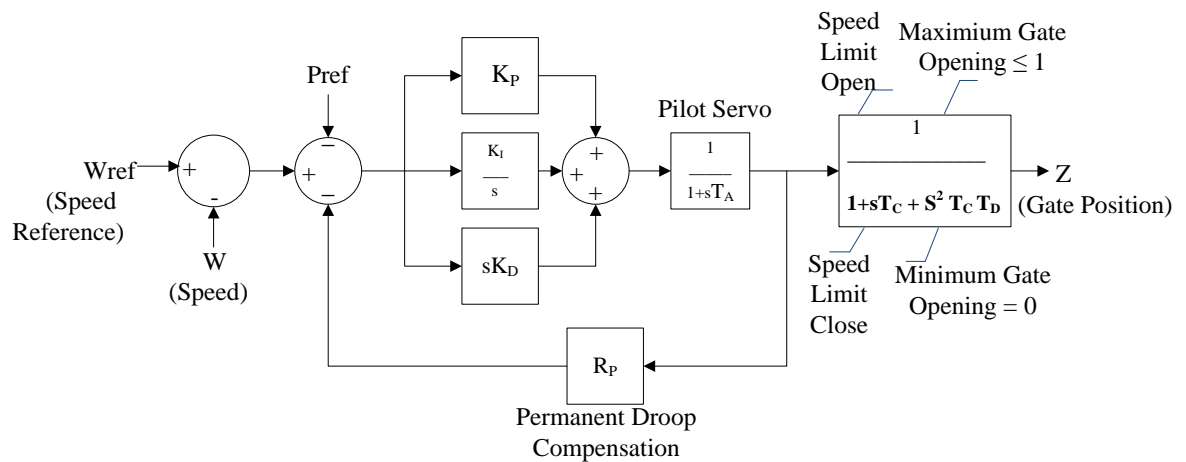


Figure 4.15 Block diagram of Electro-Hydraulic PID based governor

In Figure 4.15, T_A is the time constant of pilot valve and servomotor. T_C is a gate servo gain and T_D is the gate servomotor time constant. Permanent droop is shown by R_P . Governor model has two important parameter, maximum gate opening rate and maximum gate closing rate. These values illustrate the opening or closing of gate speed because the response in hydraulic turbine is slower than steam or gas turbine. The parameters values are given in Table 4.4 (Kundur, 1994). However, the values for P, I and D are tuned by using trial and error method to provide satisfactory results.

Table 4.4 Value of governor model parameters

Parameter	Value	Parameter	Value
K_P	2	T_C	0.2
K_I	0.35	T_D	0.2
K_D	0.9	Max gate opening	0.16
T_A	0.05	Max gate closing	0.16
R_P	0.04	Dead band value	0
Max gate position	1.0	Min gate position	0

Governor sends control signal to servomotor for controlling the turbine gate position. Servomotor controls water flow to produce power according to load demand. Transfer function for relay valve and gate servomotor is given by (Kundur, 1994):

$$\frac{G(s)}{B(s)} = \frac{K_s}{s(1 + sT_p)} \quad (4.8)$$

where, K_s is servo gain and T_p is time constant of servomotor. Servomotor controls the gate of turbine through governor and hydraulic turbine converts water head potential energy into mechanical energy. The hydraulic turbine transfer function is shown in Equation (4.9) (Kishor, et al., 2007).

$$\frac{\Delta P_m}{\Delta G} = \frac{1 - T_w s}{1 + 0.5 T_w s} \quad (4.9)$$

Where ΔP_m represents mechanical power of turbine in per unit, ΔG represents turbine gate opening in per unit and T_w represents turbine water starting time. T_w varies with load and its values lies between 0.5 s and 4.0 s. The parameter values of hydraulic turbine block used in this research are shown in Table 4.5 (Kundur, 1994).

Table 4.5 Value of hydro turbine parameters

Parameter	Value	Parameter	Value
T_w	1.0	initial output power	0.7
f_p	0.02	Initial operating head	1.0
D	0.5	Rated output power	1.0

In Table 4.5, f_p acts as a penstock head loss coefficient and D is turbine damping constant. This research considers hydraulic turbine with non-elastic water column without surge tank.

4.7 Synchronous Generator Parameters

Synchronous generators are the universal means of converting mechanical energy into electrical energy. This research employs two mini-hydro type DG, having nominal terminal voltage of 3.3kV. Synchronous generator is driven by hydraulic turbine and governor control mechanism. The generators are also equipped with excitation control as it is important requirement for maintaining voltage level within permissible limits. Figure 4.16 shows the synchronous generator with PID based governor, hydraulic turbine and excitation control modelled in PSCAD.

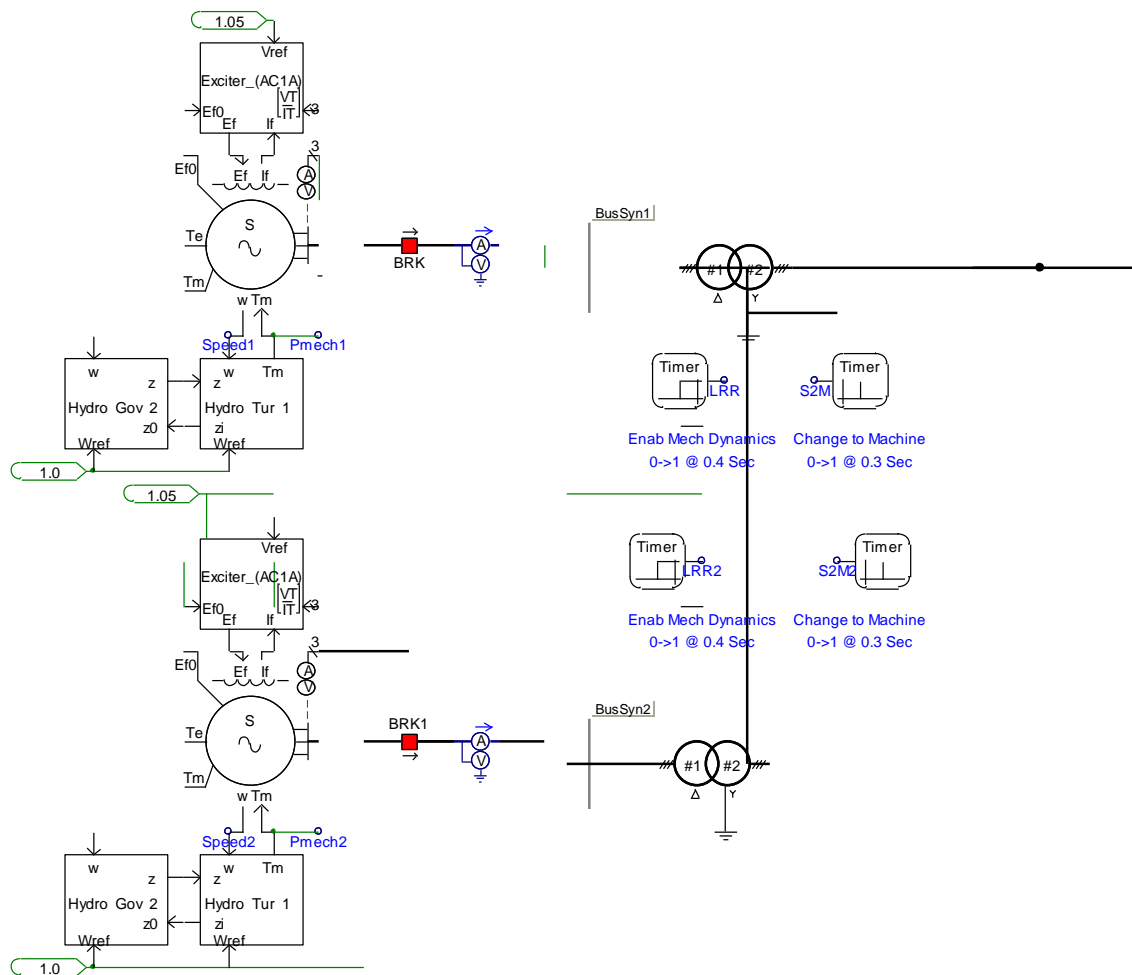


Figure 4.16 Synchronous generator model with PID based governor in PSCAD

Meanwhile, the synchronous generator model with fuzzy based governor, turbine and excitation system is shown in Figure 4.17.

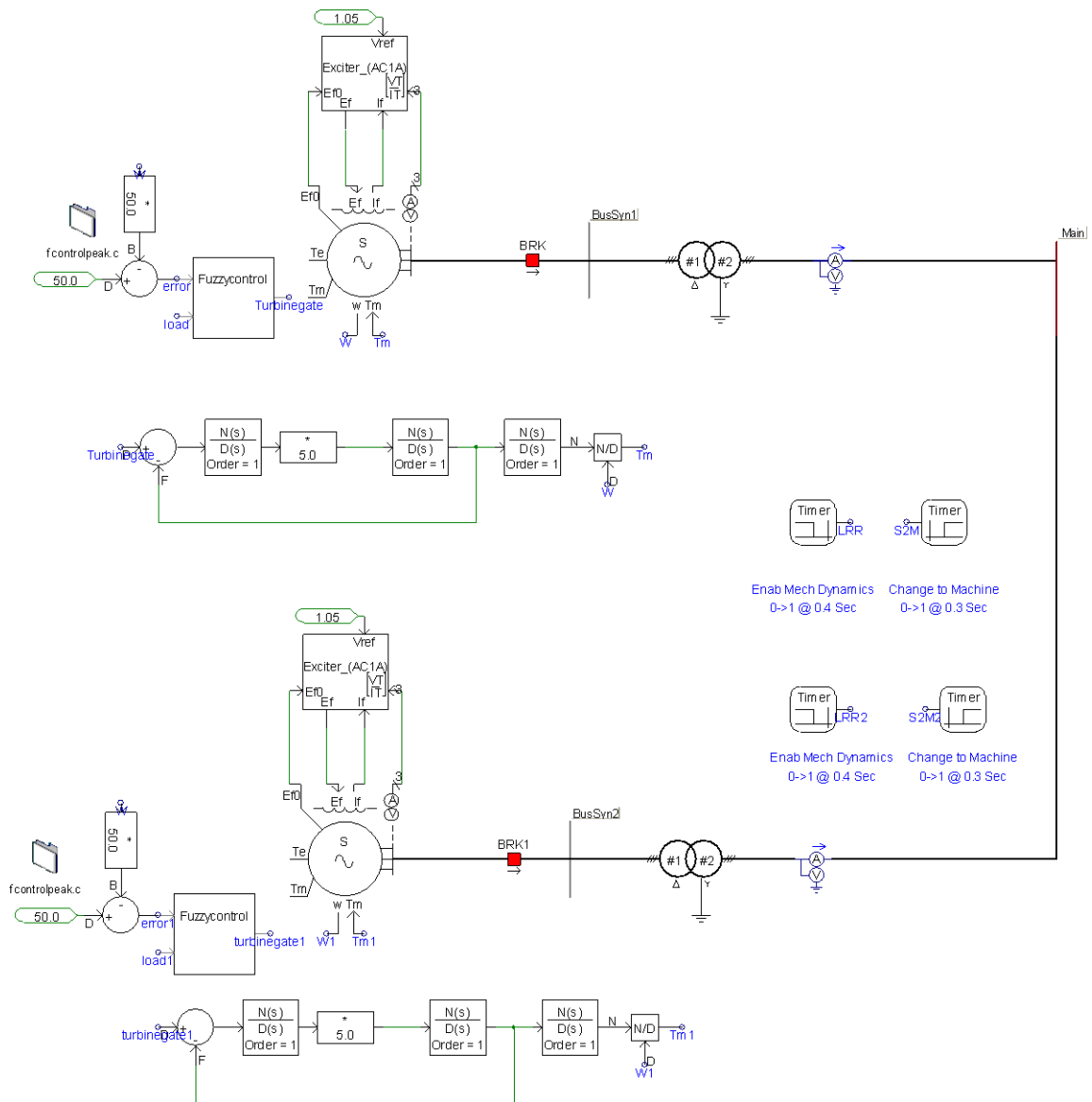


Figure 4.17 Synchronous generator model with fuzzy based governor in PSCAD

The synchronous generators have different parameters having different values. The parameters values applied in this research are based on real values of generating units implemented in TNB, Malaysia and are shown in Table 4.6.

Table 4.6 Synchronous generator parameters

Parameter	Value
Rated RMS line to line voltage	3.3 KV
Rated RMS line current	350 A
Inertia constant (H)	2.5 s
Iron loss resistance	300 p. u.
Base angular frequency	314.159 rad/s
Armature resistance [R_a]	0.01 p. u.
Potier reactance [X_p]	0.104 p. u.
Unsaturated reactance [X_d]	0.838 p. u.
Unsaturated transient reactance [X_d']	0.239 p. u.
Unsaturated transient time [T_{do}']	8.0 s
Unsaturated sub transient reactance [X_d'']	0.12 p. u.
Unsaturated sub transient time [T_{do}'']	0.05 s
Unsaturated reactance [X_q]	0.534 p. u.
Unsaturated sub transient reactance [X_q'']	0.12 p. u.
Unsaturated sub transient time [T_{qo}'']	0.1 p. u.
Air gap factor	1.0

Each generating unit is connected with step-up transformer. The step-up transformer converts generating voltage 3.3kV to 11kV voltage, as the distribution voltage level is 11kV. The transformer parameter with their values employed in this research are also based on real values of Transformers implemented in TNB, Malaysia and are shown in Table 4.7.

Table 4.7 Transformer parameters

Parameter	Value
3 phase transformer MVA	2 MVA
Primary winding type	Delta
Secondary winding type	Star
Positive sequence leakage reactance	0.08 P.U.
Air core reactance	0.2 P.U.
Inrush decay time constant	1 s
Knee voltage	1.25 P.U.
Magnetizing current	0.001%

4.8 Load Modelling and Under Ground Cable Parameters

Stable operation of a power system depends on the ability to continuously match the electrical output of generating units to the electrical load on the system. Consequently, load characteristics have an important influence on system stability. The modelling of loads is complicated because a typical load bus can composed of a large number of devices such as

fluorescent lamps, refrigerators, heaters, compressors, motors, and furnace. The exact composition of load is difficult to estimate. The load models are traditionally classified into two broad categories: Static models and dynamic models.

The static load model is applied in this research. A static model expresses the characteristics of the load at any instant of time as algebraic functions of bus voltage magnitude and frequency at that instant. The active power component P and the reactive power component Q are considered separately. Traditionally, the voltage dependency of load characteristics has been represented by the exponential model as below:

$$P = P_0 \times (V_{p.u})^a \quad (4.10)$$

$$Q = Q_0 \times (V_{p.u})^b \quad (4.11)$$

where P and Q are active and reactive components of the load when the bus voltage magnitude is V . The parameter of this model are the exponents a and b . With these exponents equal to 0, 1 or 2, the model represents constant power, constant current, or constant impedance characteristics, respectively. The exponent a (or b) is nearly equal to slope dP/dV (or dQ/dV) at $V=V_0$. For composite system loads, the exponent a usually ranges between 0.5 and 1.8; the exponent b is typically between 1.5 and 6 (Kundur, 1994).

The frequency dependency of load characteristics is usually represented by multiplying the exponential model by a factor as follows:

$$P = P_0 \left(\frac{V}{V_0}\right)^a \times (1 + K_{pf}\Delta f) \quad (4.12)$$

$$Q = Q_0 \left(\frac{V}{V_0}\right)^b \times (1 + K_{pf}\Delta f) \quad (4.13)$$

where Δf is the frequency deviation ($f - f_0$). Typically, K_{pf} ranges from 0 to 3.0, and K_{qf} ranges from -2.0 to 0. The parameters values for static load used in this research are shown in Table 4.8.

Table 4.8 Static load parameters

Parameter	Value	Parameter	Value
dP/dV	1	dP/df	1
dQ/dV	2	dQ/df	-1

The underground cable size is 185sqmm in distribution network between the buses and its specification is given below in Table 4.9.

Table 4.9 Cable specification

Description	Value	Description	Value
Conductor material	Aluminium	Star reactance at 50 Hz/Km, Ω	0.092
A.C. resistance/Km, Ω	0.211	Star capacitance/Km, μF	0.430

Table 4.10 shows the load values and its category with active and reactive power separately. The load values for base load and peak load are also provided. The load category will be applied for load shedding priority. Loads are ranked based on their prioritization. Proposed load shedding scheme disconnect the load with lowest ranked first

(load ranked 1), according to order of priority and load with high ranked will be shed at the last.

Table 4.10 Load values and ranking table

Load Ranked	Bus Number	Peak Load		Base Load		Load
		P(MW)	Q(MVAR)	P(MW)	Q(MVAR)	Category
1	1013	0.0684	0.0423	0.0456	0.0282	Non-vital
2	1141	0.0795	0.0495	0.0531	0.033	Non-vital
3	1012	0.0795	0.0495	0.0531	0.033	Non-vital
4	1050	0.1095	0.0576	0.063	0.0384	Non-vital
5	1047-1079	0.1794	0.0792	0.11721	0.07281	Non-vital
6	1057	0.189	0.1152	0.126	0.0768	Non-vital
7	1058	0.198	0.123	0.132	0.0819	Non-vital
8	1010-1039	0.234	0.1101	0.15009	0.0933	Non-vital
9	1064	0.1488	0.0867	0.093201	0.057801	Semi-vital
10	1018	0.1743	0.108	0.11619	0.072	Semi-vital
11	1154	0.2097	0.1275	0.1401	0.0849	Semi-vital
12	1004	0.2121	0.1314	0.14151	0.0876	Semi-vital
13	1046	0.2535	0.1578	0.1701	0.1053	Semi-vital
14	1020	0.2745	0.1716	0.1845	0.11439	Semi-vital
15	1029	0.3468	0.2148	0.2313	0.1431	Semi-vital
16	1019	0.1902	0.099	0.10671	0.06609	Vital
17	1151	0.2208	0.0996	0.107199	0.06639	Vital
18	1056	0.345	0.3282	0.35259	0.2187	Vital

CHAPTER 5

RESULTS AND DISCUSSIONS

In the previous chapter, modelling of proposed fuzzy based load frequency control technique and load shedding scheme has been presented. The scheme is tested and validated by implementing it into a Malaysian distribution network. PSCAD/EMTDC software is used to model and simulate the test system. This chapter presents and discuss the test system, results and discussions of these case studies.

5.1 Test System for the Proposed Fuzzy Based LFC and UFLS Scheme

The test system for analyzing the proposed fuzzy based load frequency control (LFC) scheme and under frequency load shedding (UFLS) scheme consists of a DG system having two mini-hydro power plants are modelled in PSCAD/EMTDC. Each DG unit has 2 MVA capacity (maximum power dispatch is 1.8MW) and are working in parallel operation. The distribution system consists of 27 buses, 20 lumped loads, 16 remote circuit breakers (RCB) and is islanded from the main grid. The distribution line is modelled by nominal PI model having length not greater than 6 km. The distribution network is shown in Figure 5.1.

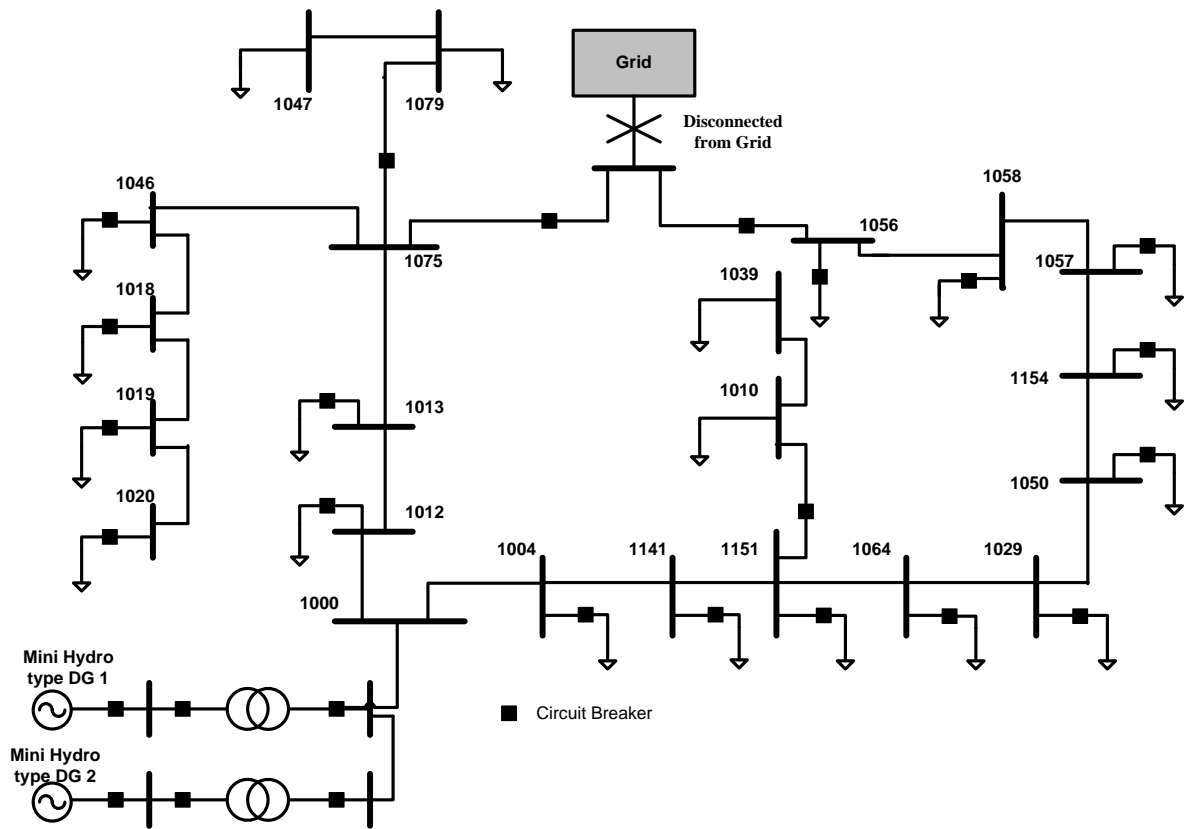


Figure 5.1 Mini hydro power plants connected to islanded distribution network

To evaluate the effect of governor for load frequency control (LFC) technique, DG units are tested with fuzzy based governor and PID based governor. The test system designed in PSCAD with PID as governor for load frequency control (LFC) is shown in Figure 5.2(a).

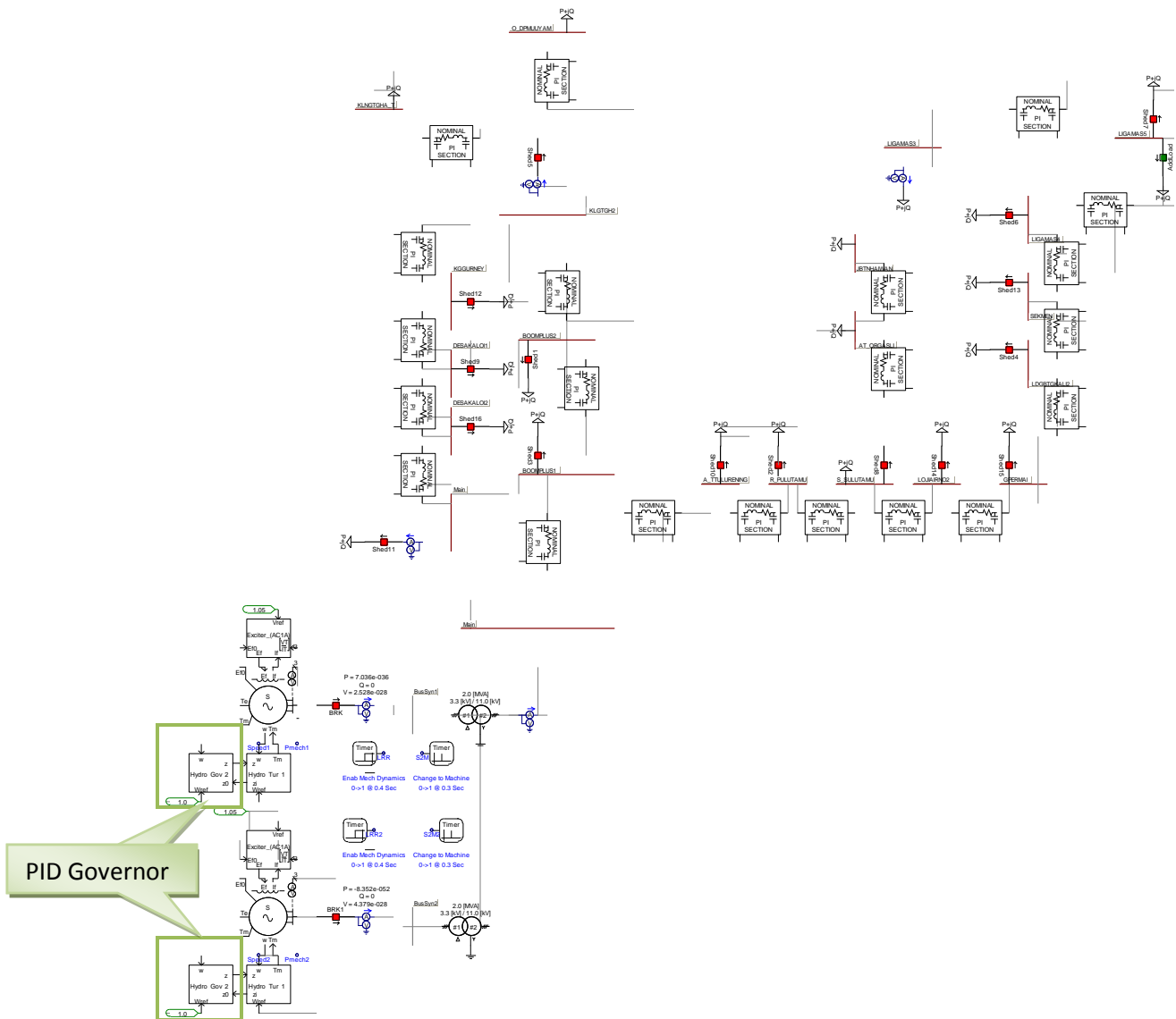


Figure 5.2 (a) LFC test system with PID based governor

The test system modelled in PSCAD with fuzzy based governor for load frequency control (LFC) is shown in Figure 5.2 (b).

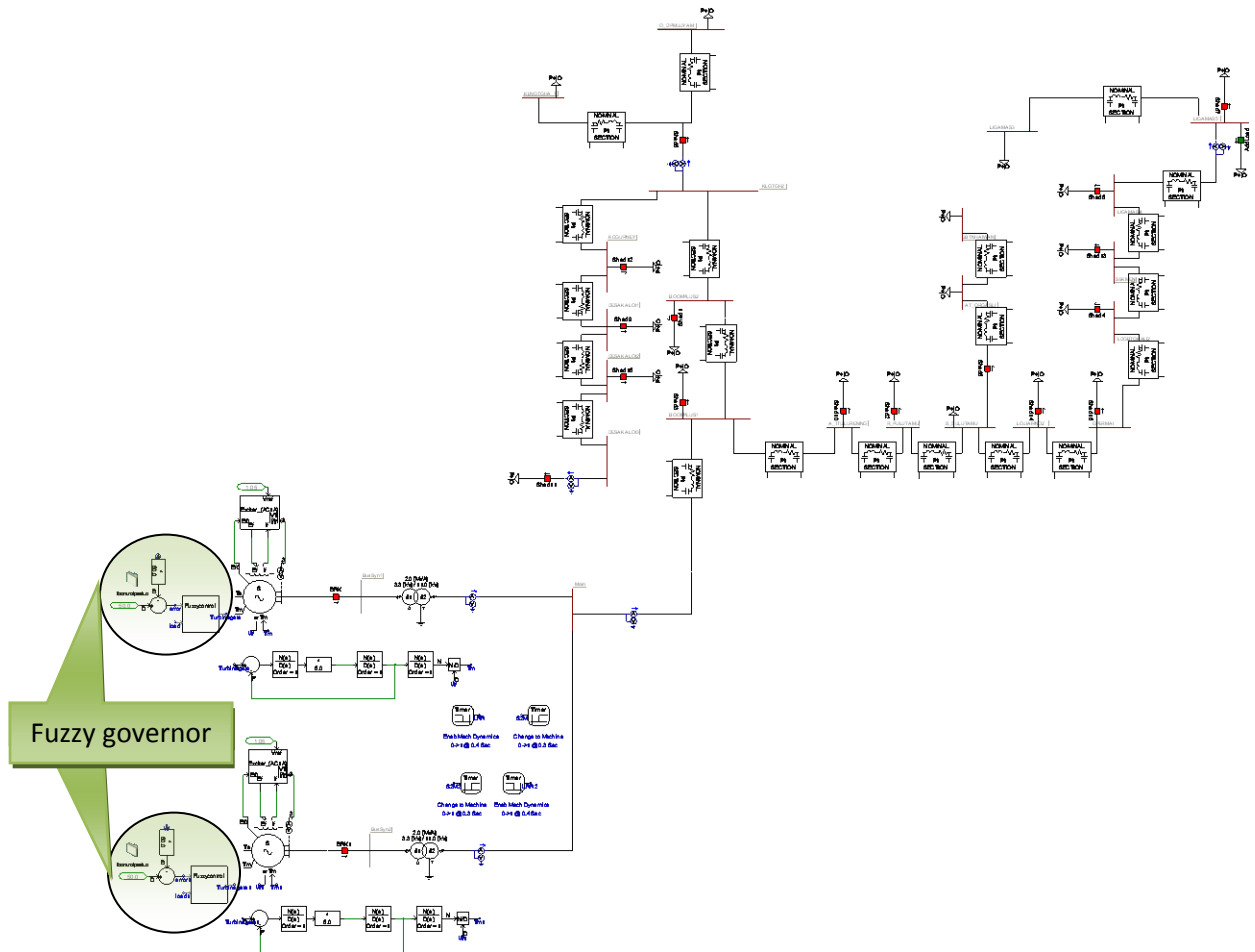


Figure 5.2 (b) LFC test system with fuzzy based governor

The test system for fuzzy based UFLS scheme has the same configuration as described above in Figure 5.1. Apart from this, the distribution network has load profile of base load capacity and peak load capacity. The loads are ranked based on their load priority and load look-up table is created according to their prioritization as shown in Table 4.10. The load priority is created by considering active power value of each load. Each node is connected with remote circuit breaker (RCB) that can be remotely controlled for load shedding purposes.

The amount of load to be shed greatly depends upon the fast utilization of DG spinning reserve, whereas the fast utilization of spinning reserve depends upon the governor response. In order to observe governor response, the UFLS scheme is tested with PID based governor and fuzzy based governor. The objective of this study is to find, which governor can provide efficient control, fast utilization of spinning reserve resulting in lesser load to be shed. The test system with fuzzy based governor and UFLS scheme is shown in Figure 5.3(a). The test system with PID based governor and UFLS scheme is shown in Figure 5.3 (b).

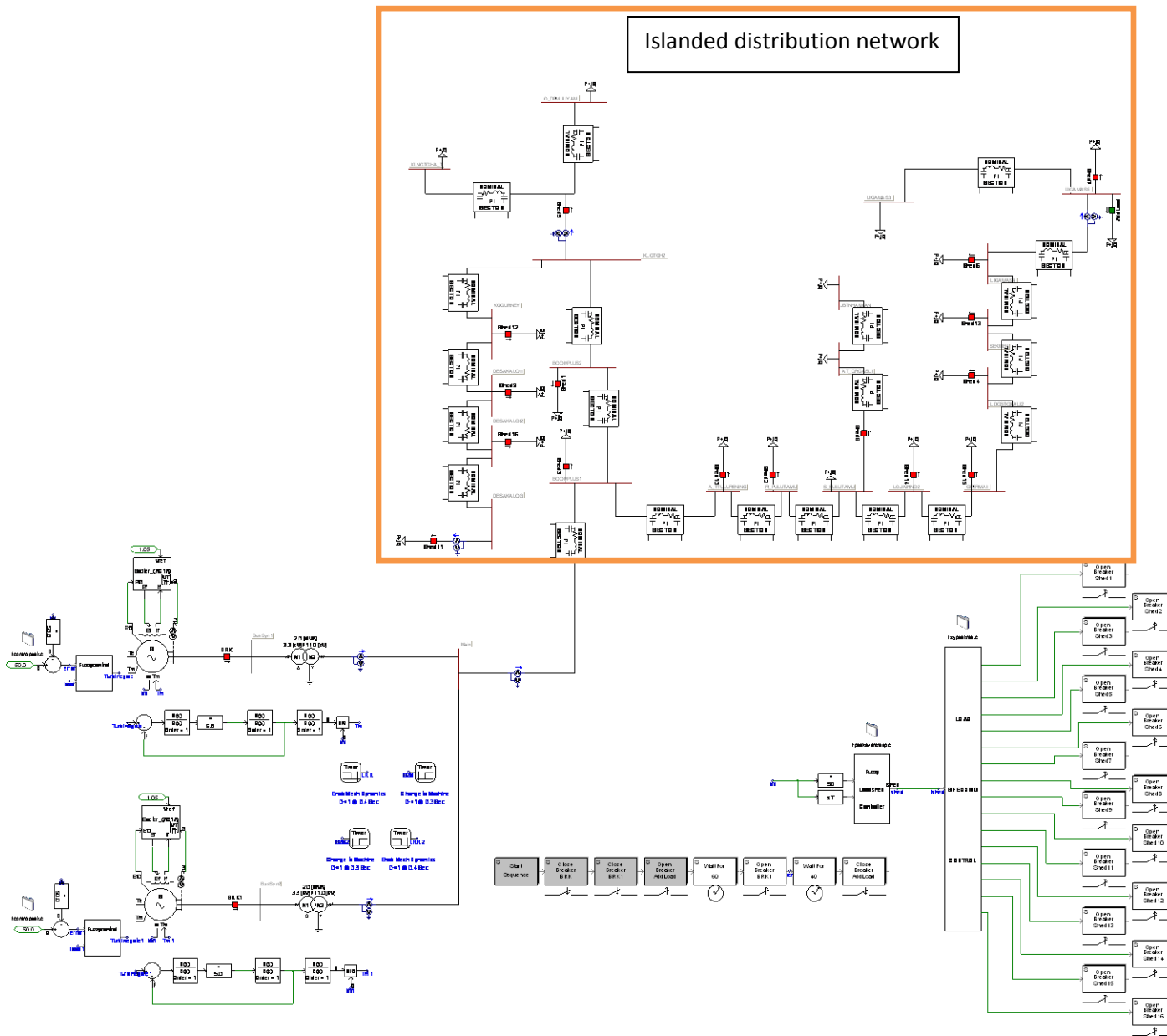


Figure 5.3 (a) Test system with fuzzy based governor and UFLS scheme

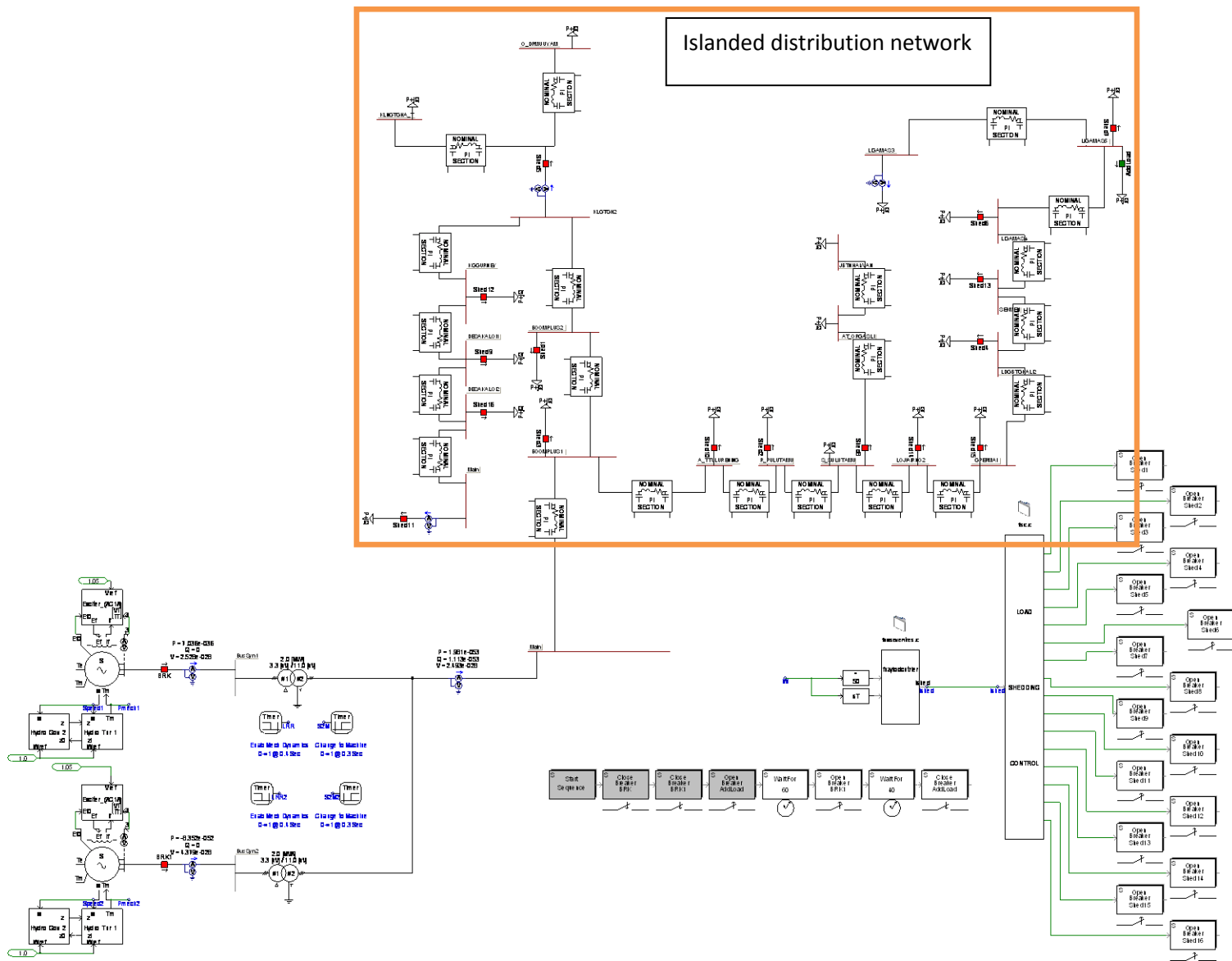


Figure 5.3(b) Test system with PID based governor and UFLS scheme

5.2 Case Studies

This research includes the case studies of Load frequency control (LFC) and under frequency load shedding (UFLS) scheme. Under frequency load shedding scheme involves Event based and Response based case studies. All case studies of load frequency control and load shedding scheme are tested on islanded distribution network connected with DG's. The case studies are tested with two types of governors; one PID based governor and other fuzzy based governor. The descriptions of case studies are summarized in Table 5.1.

Table 5.1 Description of case studies for LFC and UFLS scheme

Case Studies	Description
Case I	Load frequency control (1) 10 %-25 % load disconnected. (2) 10 %-25 % load connected.
Case II	Event Based Load Shedding (1) Event Based at Base Load Capacity (2) Event Based at Peak Load Capacity
Case III	Response Based Load Shedding (1) Response Based at Base Load Capacity (2) Response Based at Peak Load Capacity
Case IV	Event Based and Response Based Load Shedding (1) Event Based and Response Based at Base Load Capacity (2) Event Based and Response Based at Peak Load Capacity

5.2.1 Case I: Load Frequency Control

5.2.1.1 10 % - 25 % Load Disconnected

In this case, the mini hydro power plants type DG are operating in interconnected mode and supplying power to islanded distribution network up to 80% of their capacity. To test the governor response in terms of overshoot and settling time, 10%, 20% and 25% of loads are disconnected. The aim of this case is to determine how much load can be disconnected at once, while keeping frequency overshoot within 52.5Hz limit. Since, if frequency crosses the 52.5Hz, DG unit will be tripped due to its setting for safety reason. Otherwise, this will result in destruction of turbine blades. When 10%, 20% and 25% of loads are disconnected, it results in an overshoot in system frequency. Frequency response of DG units with both PID and fuzzy based governor is tested and are shown in Figure 5.4.

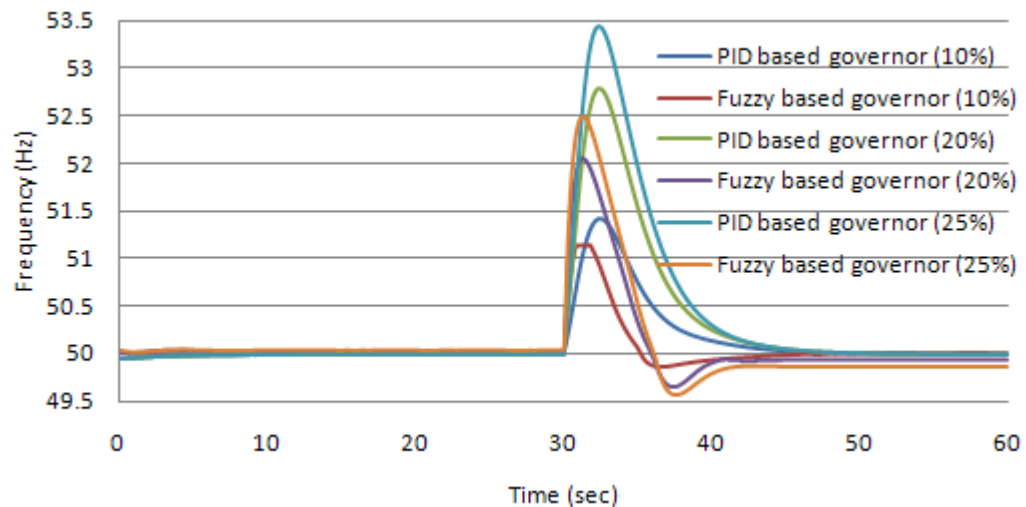


Figure 5.4 Frequency responses at 10 % - 25 % load reduction

It can be observed from Figure 5.4, that PID based governor takes 17.4 s, 18 s and 19 s

to stabilize the DG frequency during 10%, 20% and 25% load reductions respectively. Whereas, fuzzy based governor takes 14 s, 14.75 s and 15 s to stabilize the DG frequency for similar load reduction. The frequency overshoot of DG with PID based governor during 10%, 20% and 25% load reductions is 51.4 Hz, 52.5 Hz and 53.46 Hz respectively. Whereas, frequency overshoot of DG with fuzzy based governor for similar load reduction are 51.13 Hz, 51.9 Hz and 52.35 Hz. Thus, DG with fuzzy based governor has smaller frequency overshoot and shorter settling time than DG with PID based governor.

5.2.1.2 10 % - 25 % Load Connected

In this case, the DG units are supplying power to distribution network which is islanded from the main grid. To test the governor responses in terms of undershoot and settling time, 10%, 20% and 25% of loads are connected. The aim of this case is to determine maximum load that can be connected at once, while keeping frequency undershoot within 47.5 Hz limit. Since, if frequency goes below the 47.5 Hz limit, DG unit will be tripped due to its setting for safety reason as described in section 3.3. When 10%, 20% and 25% of loads are connected, it results in an undershoot in system frequency. Frequency response of DG units with both PID and fuzzy based governor is tested and are shown in Figure 5.5.

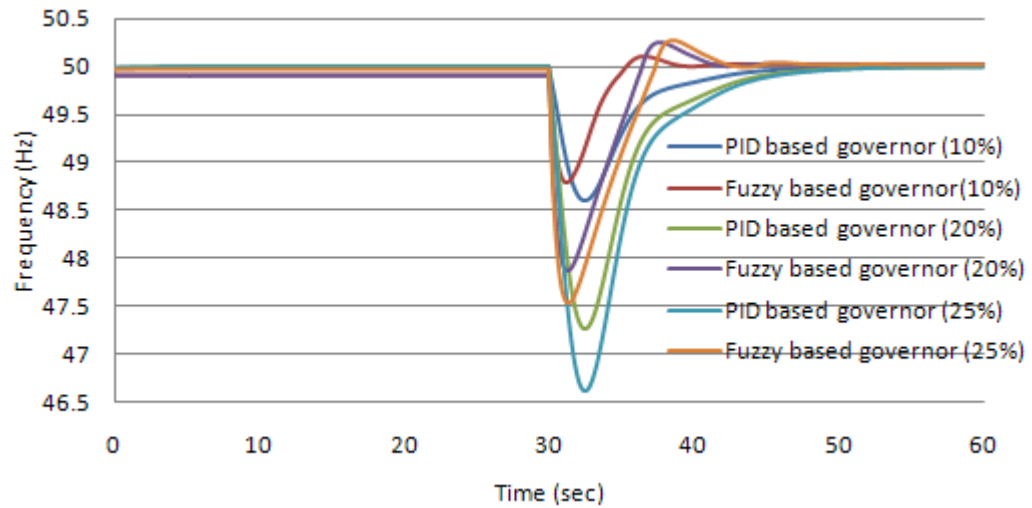


Figure 5.5 Frequency responses at 10 % - 25 % load addition

From the Figure 5.5, it can be observed that PID based governor takes 14.21 s, 16 s and 20 s to stabilize the DG frequency at 10%, 20% and 25% load addition respectively. Whereas, fuzzy based governor takes 10 s, 10.5 s and 14.5 s to stabilize frequency for similar load addition. The frequency undershoot of DG with PID based governor during these load addition are 48.6 Hz, 47.32 Hz and 46.63 Hz. Whereas, frequency undershoot of DG with fuzzy based governor at these load addition is 48.8 Hz, 47.8 Hz and 47.52 Hz. Thus, frequency response of DG with fuzzy based governor is again much better having smaller undershoot and shorter settling time than DG with PID based governor.

Figure 5.6 compares the DG frequency overshoot with PID based governor and fuzzy based governor at various load reductions.

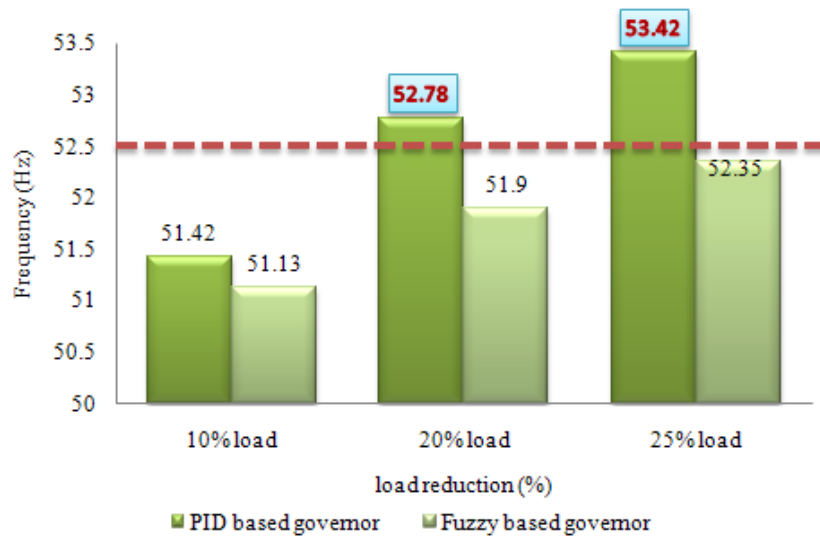


Figure 5.6 Frequency overshoot graph at different load reduction

The frequency undershoot response of DG with PID based governor and fuzzy based governor at various load additions is given in Figure 5.7. It can be noticed from Figure 5.7, that DG with fuzzy based governor has again smaller frequency undershoot range than a DG with PID based governor in all load additions.

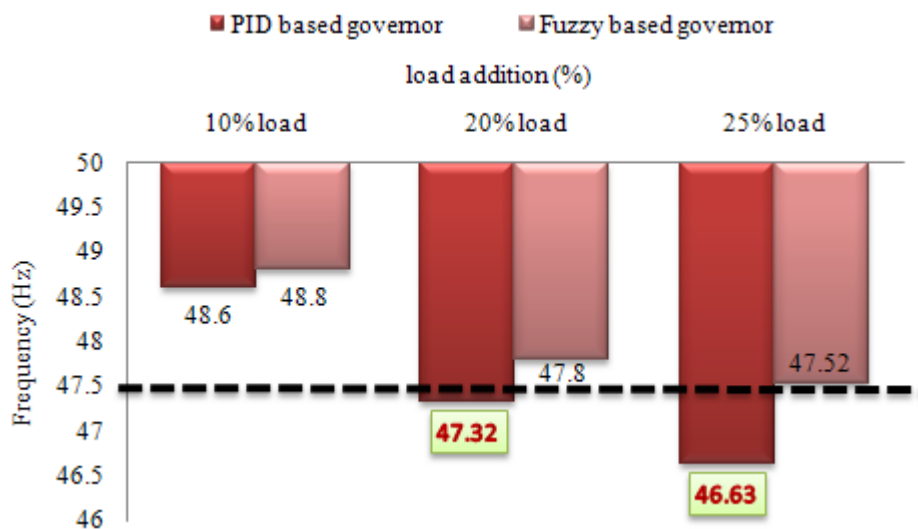


Figure 5.7 Frequency undershoot graph at different load addition

The important point to be noted in these cases is that, frequency response of DG with PID based governor during 20% to 25% load addition and reduction goes beyond stable frequency limit of 52.5 Hz and 47.5 Hz respectively. When DG frequency crosses these limits, DG will automatically trip off due to its setting for safety reason. Whereas, the frequency response of DG with fuzzy based governor has shown that on addition and reduction of 20% and 25% load, DG frequency still remain within the stable overshoot and undershoot frequency limit of 52.5 Hz and 47.5 Hz. Thus, fuzzy based governor provides robust and efficient frequency control and ensures continuous supply of power during 20% and 25% load variations. Whereas, DG with PID based governor fail to supply power at 20% load variation.

5.2.2 Case II: Event Based Load Shedding

5.2.2.1 Event Based at Base Load Capacity

To simulate Event based load shedding case at Base load capacity (2.5 MW), one of the DG unit is tripped-off from the islanded distribution system. Since, the loads in islanded system are supplied by two mini-hydro DG's, the loss of one DG will cause a great impact to islanded system. As a result, all load is shifted to the remaining operating DG unit. Since, load is beyond the maximum capacity of DG unit and need to be shed in order to allow the DG unit operating continuously. If load shedding scheme is not applied, frequency will drop below 47.5 Hz and will never be recovered, resulting in power blackouts as shown in Figure 5.8.

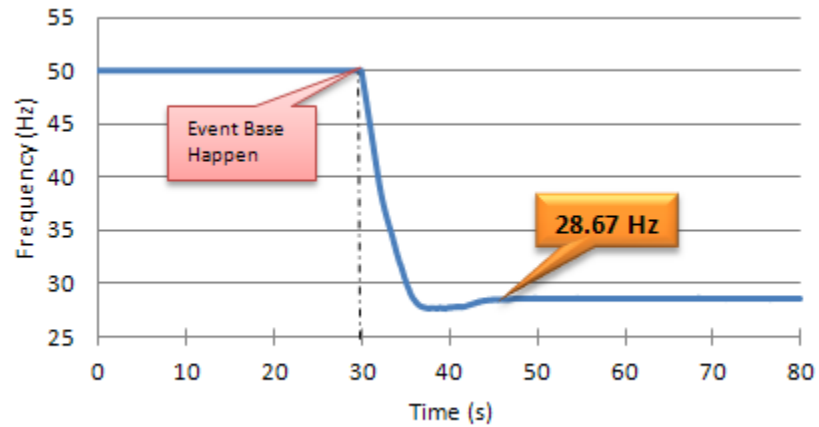


Figure 5.8 Event based case when load shedding scheme is not applied

Hence, load shedding scheme is necessary in order to keep the frequency within the acceptable limits and prevent power system from power collapse. When Event based load shedding is applied at $t=30$ s by tripping one DG unit. The FLLSC checks first frequency limit of 49.5 Hz. After checking this, FLLSC check about type of load disturbance applied on islanded distribution system. FLLSC by monitoring RCB status of DG units determines that system encountered Event based load disturbance. FLLSC estimates the amount of load to be shed and sends signal to LSCM, which immediately trip significant number of load feeders to stabilize the frequency and voltage of DG. The frequency response of DG with PID and fuzzy based governor for this case is shown in Figure 5.9.

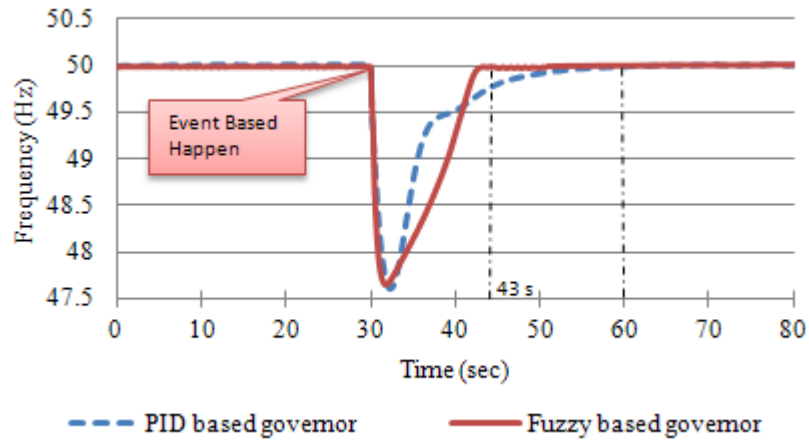


Figure 5.9 Frequency response during Event based at base capacity

From the Figure 5.9, it can be observed that when Event based happened at $t=30$ s, DG with fuzzy based governor has frequency undershoot of 47.65 Hz. The frequency fully recovered to 50 Hz after 13 s. Whereas, DG with PID based governor has frequency undershoot of 47.62 Hz and frequency fully recovers to 50 Hz after 30s. Hence, DG with fuzzy based governor has smaller frequency undershoot and shorter settling time than a DG with PID based governor. In order to observe the voltage stability of the system, the voltage magnitude of Buses located at nearest distance (Bus number 1000), and at far distance (Bus number 1010, 1020 and 1075) are considered in this case to show voltage stability. Figure 5.10 depicts the voltage magnitude on these buses when system is tested with PID based governor, whereas Figure 5.11 shows the voltage magnitude when system is tested with fuzzy based governor.

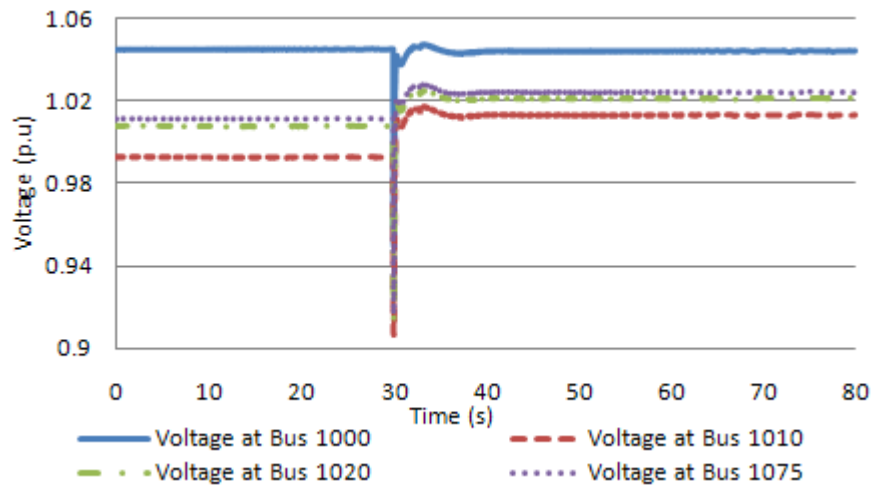


Figure 5.10 Voltage graph during Event Based at Base capacity (PID governor system)

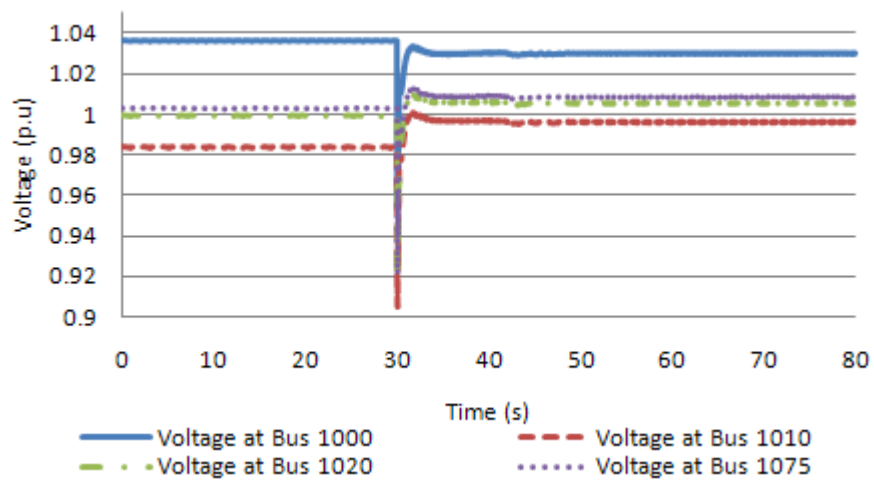


Figure 5.11 Voltage graph during Event Based at Base capacity (fuzzy governor system)

It can be observed from Figure 5.10 that when system encountered Event based disturbance at $t=30$ s, the voltage of Bus 1010 located at far distance goes to 0.907 p.u and recovers to 0.95 p.u within 0.15 s. In Figure 5.11, the voltage of Bus 1010 slightly goes to 0.905p.u and recovers to 0.95p.u within 0.16 s. Hence, proposed load shedding scheme also

ensures voltage stability in this case. The power graph of DG with PID based and fuzzy based governor is shown in Figure 5.12.

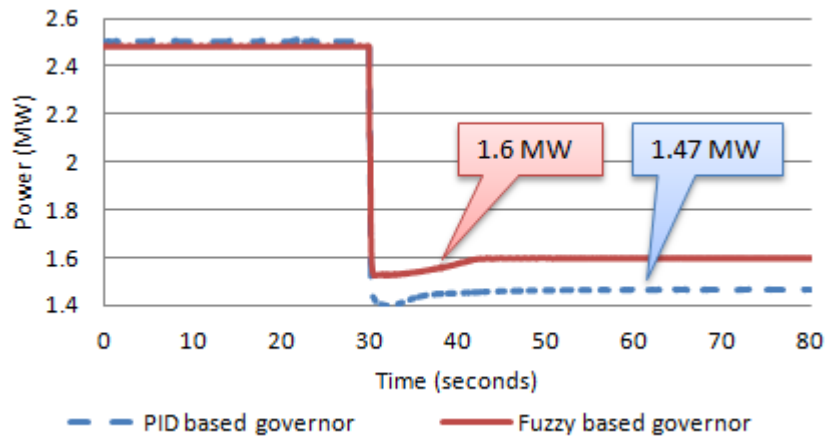


Figure 5.12 Power graph during Event based at base capacity

It can be observed from Figure 5.12 that PID based governor enable DG to supply 73.5% (1.47 MW) load. Whereas, fuzzy based governor enable DG to supply 80% (1.6 MW) load. Thus, fuzzy based governor enables the DG unit to utilize 6.5% more spinning reserve of generating system than PID based governor. The islanded distribution network with operated breakers during Event based load shedding case is shown in Figure 5.13.

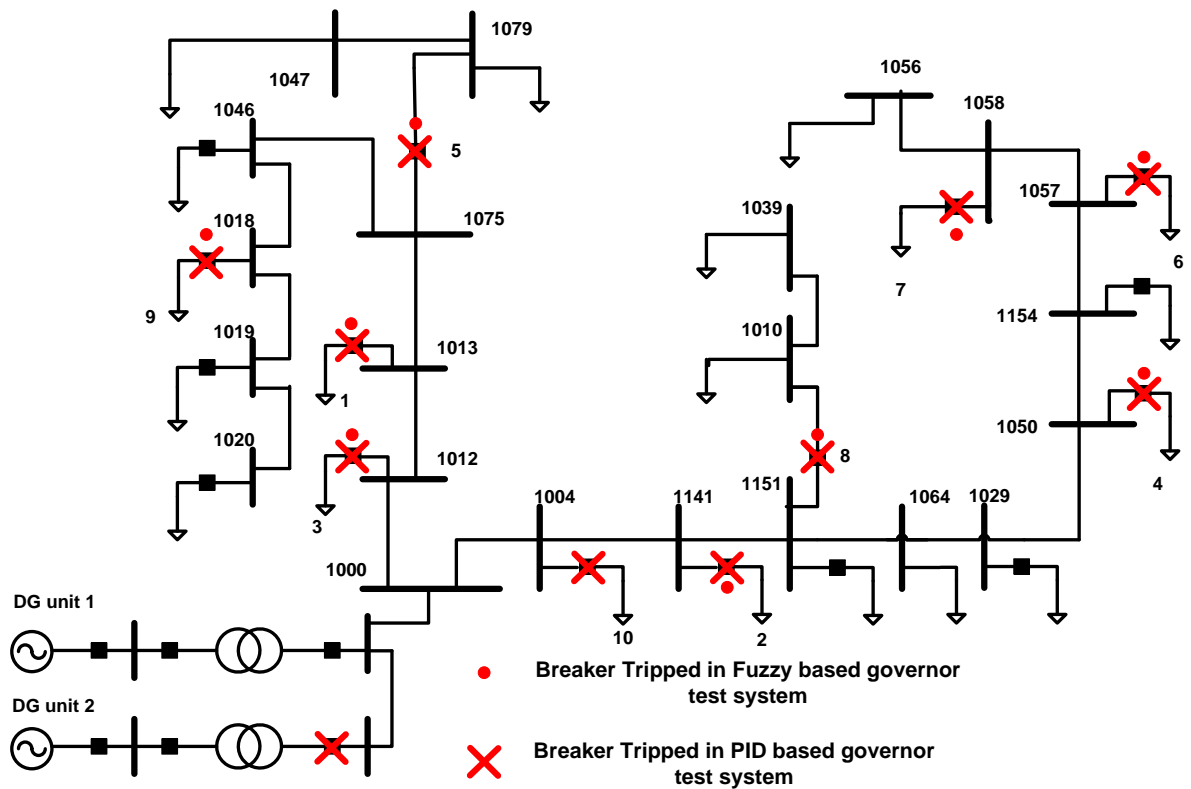


Figure 5.13 Breakers operated during Event based at base capacity

The load shedding values, power saving and breakers tripped during Event based load shedding case are shown in Table 5.2.

Table 5.2 Load Shedding values during Event based at base capacity

Governor	Power Supplied	Amount of Load Shed	Power saving	Total no. of Breakers Operated
PID based governor	1.47MW (73.5%)	1.03MW	-	10
Fuzzy based governor	1.6MW (80%)	0.9MW	6.5 %	9

It can be observed that FLLSC provides load shedding for both PID and fuzzy governor based DG. However, fuzzy based governor due to its fast response and robust control enable DG unit to utilize 6.5% more spinning reserve than PID based governor. Due to this, a DG with fuzzy based governor requires lesser load to be shed (0.9 MW) than a DG with PID based governor (1.03 MW).

5.2.2.2 Event Based at Peak Load Capacity

To simulate Event based load shedding case at Peak load capacity (3.6 MW), one of the DG unit is tripped-off from islanded distribution system. Event based load shedding is applied at $t=30$ s. The frequency response and power graph of DG with PID and fuzzy based governor for this case is shown in Figure 5.14-5.15.

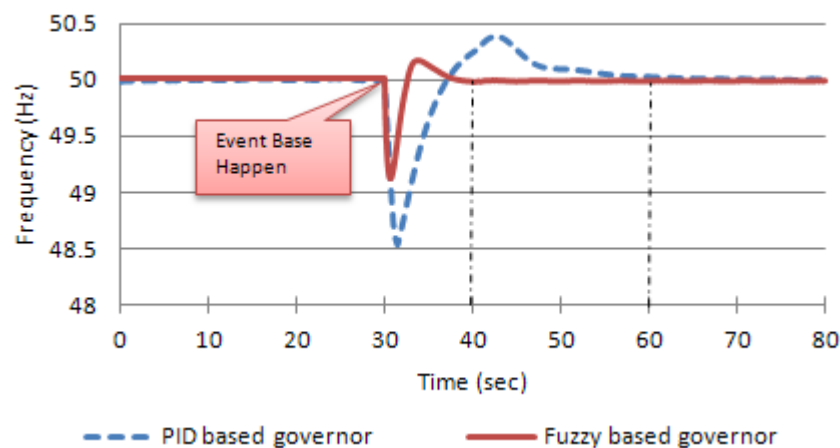


Figure 5.14 Frequency response during Event based at peak capacity

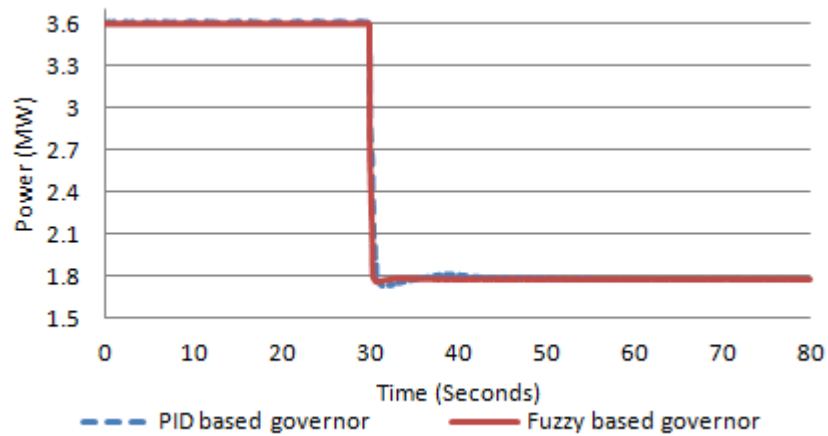


Figure 5.15 Power graph during Event based at peak capacity

From the Figure 5.14 and Figure 5.15, it can be observed that when Event based happened at $t=30$ s, DG with PID based governor recovers frequency to 50 Hz after 30 s and enables DG to supply 90% (1.8 MW) load. Whereas, fuzzy based governor stabilizes the DG frequency recovers to 50 Hz after 10 s and enables DG to supply also 90% (1.8 MW) load. The voltage magnitudes at different Buses are shown in Figure 5.16-5.17. Figure 5.16 depicts the voltage magnitude on these buses for this case when system is tested with PID based governor, whereas the Figure 5.17 shows the voltage magnitude when system is tested with fuzzy based governor.

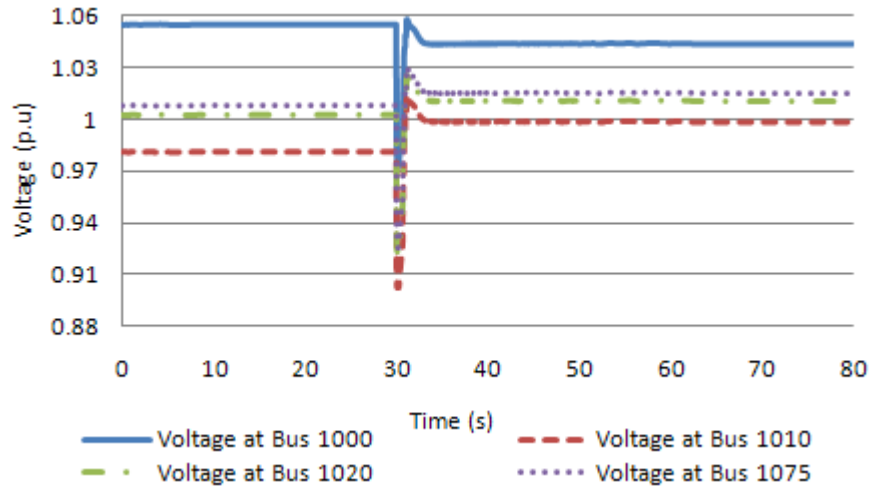


Figure 5.16 Voltage graph during Event Based at Peak capacity (PID governor system)

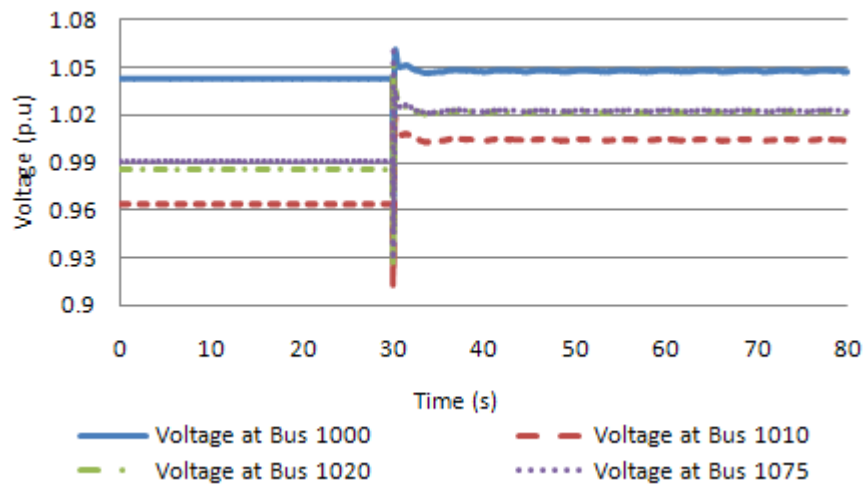


Figure 5.17 Voltage graph during Event Based at Peak capacity (fuzzy governor system)

It can be observed from Figure.5.16 that when system encountered Event based disturbance at $t=30$ s, the voltage of Bus 1010 located at far distance slightly goes to 0.9017p.u and recovers to 0.95p.u within 0.74 s. In Figure 5.17 voltage of Bus 1010 goes to 0.908p.u and recovers to 0.95p.u within 0.15 s. Hence, proposed load shedding scheme also

ensures voltage stability in this case. In Event based load shedding at peak capacity case, 11 breakers are operated to stabilize the frequency within the acceptable values.

The distribution network with operated breakers during this load shedding case is shown in Figure 5.18.

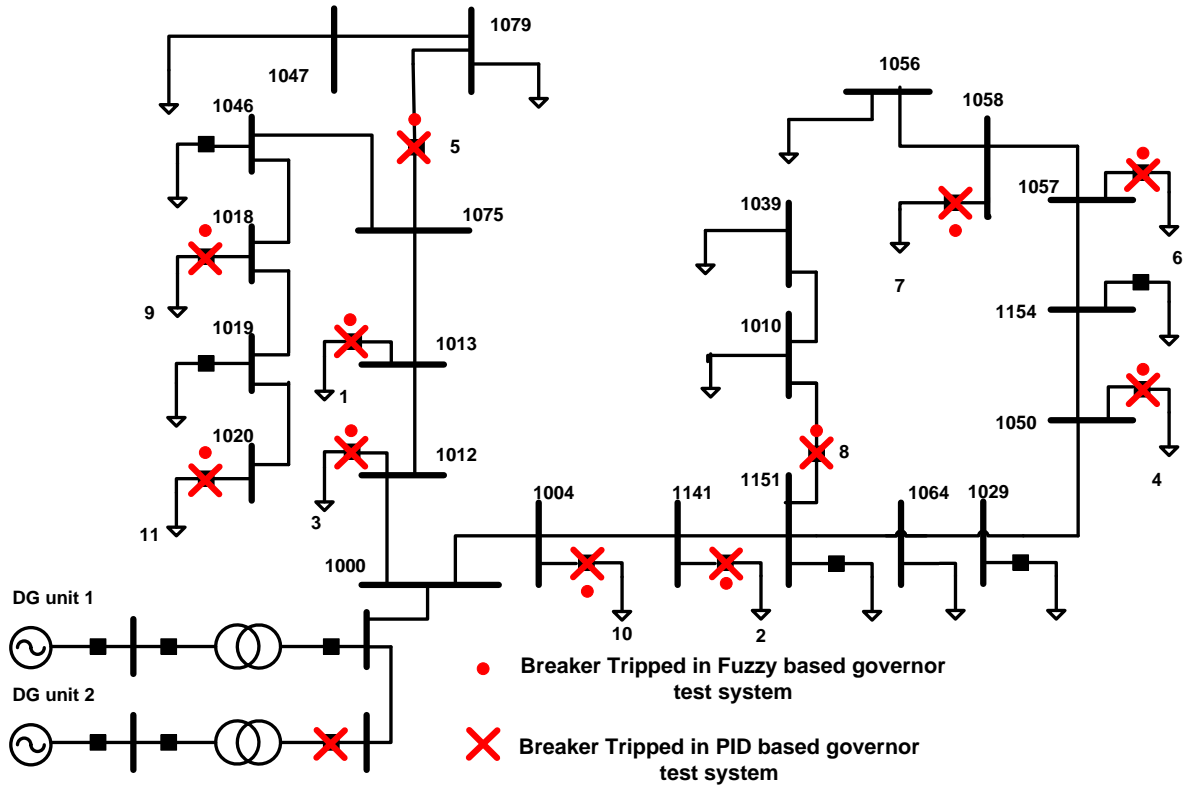


Figure 5.18 Breakers operated during Event based at peak capacity

The load shedding values, and breakers tripped during this load shedding case are shown in Table 5.3.

Table 5.3 Load Shedding values during Event based at peak capacity

Governor	Undershoot	Stabilizing Time	Power Supplied	Amount of Load Shed	Total no. of Breakers Operated
PID based governor	48.56Hz	30 s	1.8MW (90%)	1.8MW	11
Fuzzy based governor	49.13Hz	10 s	1.8MW (90%)	1.8MW	11

From Table 5.3, it can be observed that the DG unit supplies same power with both PID and fuzzy based governor. However, DG with fuzzy based governor has quite smaller frequency undershoot and shorter settling time than a DG with PID based governor. In this case, LSCM tripped same number of breakers for fuzzy based governors. It is due to the limitation of load ranking values as shown in Table 4.10. Since, after 10th Peak load ranking, 11th load rank has value of 0.2745MW. If LSCM did not trip this breaker, the total load on DG unit will cross maximum limit of 2MW ($1.8\text{MW} + 0.2745\text{MW} = 2.07045\text{MW}$). Thus, LSCM tripped 11th load rank to stabilize the frequency, enabling the DG to continue supply the power and preventing it from power collapse.

5.2.3 Case III: Response Based Load Shedding

5.2.3.1 Response Based at Base Load Capacity

To simulate Response based load shedding case at Base load capacity (2.5 MW); a load increment of 1 MW is applied at bus number 1058 in islanded distribution network. In

this case, both DG units are operating at their base capacity. Upon addition of 1 MW load disturbance, total load becomes 2.5 MW + 1 MW = 3.5 MW. Although, total load amount is less than the maximum capacity of both DG units (4MW), load shedding is still required. If load shedding scheme is not applied, frequency will drop less than 47.5 Hz as shown in Figure 5.19. If frequency crosses the limit of 47.5 Hz, DG unit will trip due to its setting for safety reason. Hence, load shedding scheme is necessary in order to keep DG units operating.

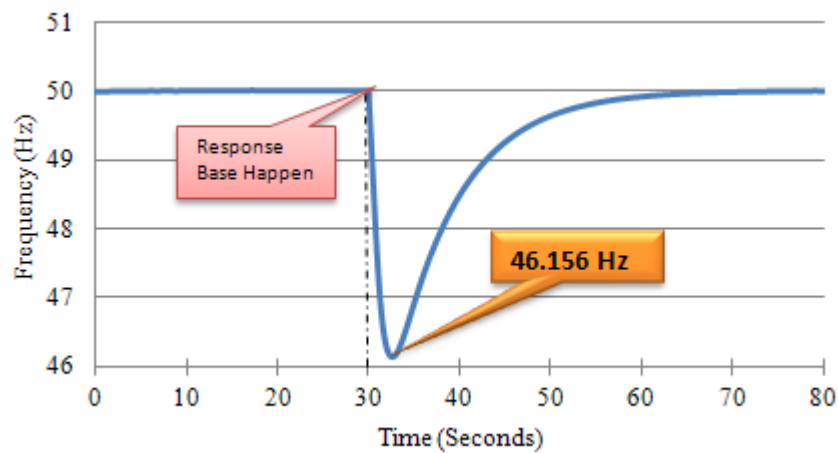


Figure 5.19 Response based case when load shedding scheme is not applied

By adapting proposed UFLS scheme, FLLSC again checks for frequency limit of 49.5 Hz. After checking this, FLLSC check about type of load disturbance applied on system. FLLSC by monitoring RCB status of DG units determines that system encountered Response based load disturbance. The FLLSC by measuring frequency and df/dt , estimates the amount of load to be shed for this case. If estimated amount is greater than ΔP_{max} , FLLSC sends signal to LSCM, which immediately trip significant number of load feeders to stabilize the frequency. However, if estimated amount is less than ΔP_{max} , FLLSC does

not send signal to LSCM, the DG unit's remains operating without requiring any load to be shed. The frequency response of DG with PID and fuzzy based governor for response base case are shown in Figure 5.20.

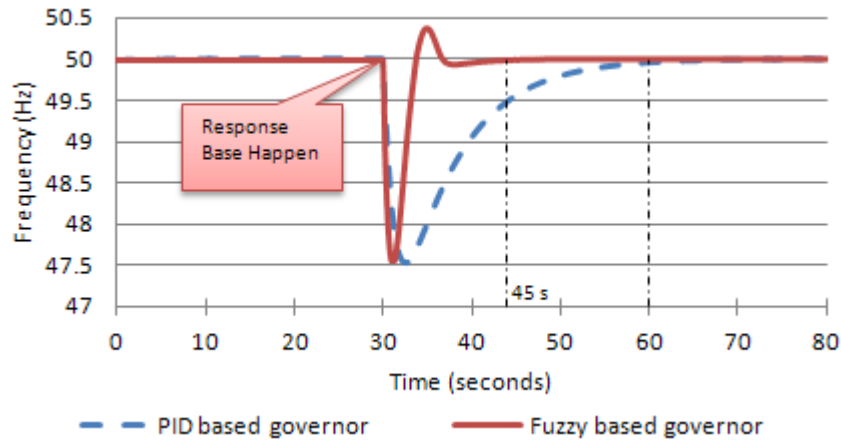


Figure 5.20 Frequency response during Response based at base capacity

From Figure 5.20, it can be observed that when response base happened at $t=30$ s, DG frequency with PID based governor has undershoot of 47.52 Hz. The frequency fully recovered to 50 Hz after 30 s. However, with fuzzy based governor, DG frequency has undershoot of 47.56 Hz and frequency recovered to 50 Hz after 15 s. The voltage stability of islanded distribution network for this case is shown in Figure 5.21 and 5.22. Figure 5.21 depicts the voltage magnitude on these buses for this case when system is tested with PID based governor, whereas the Figure 5.22 shows the voltage magnitude when system is tested with fuzzy based governor.

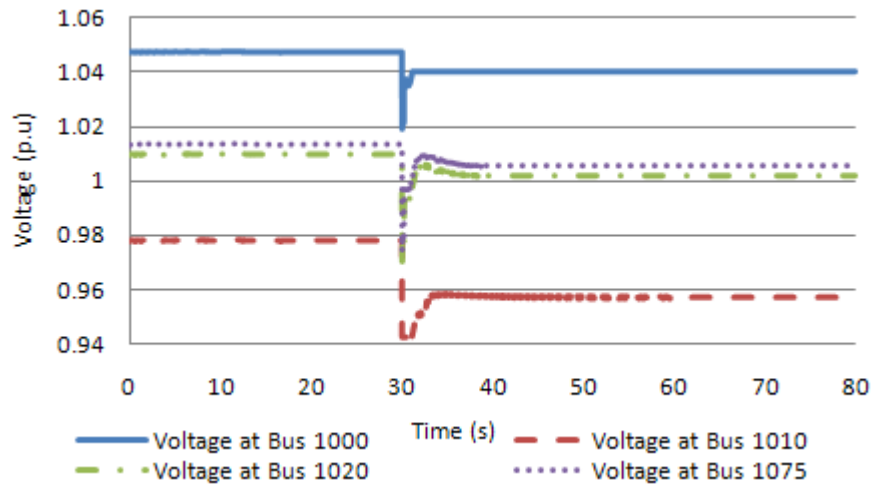


Figure 5.21 Voltage graph in Response Based at Base capacity (PID governor system)

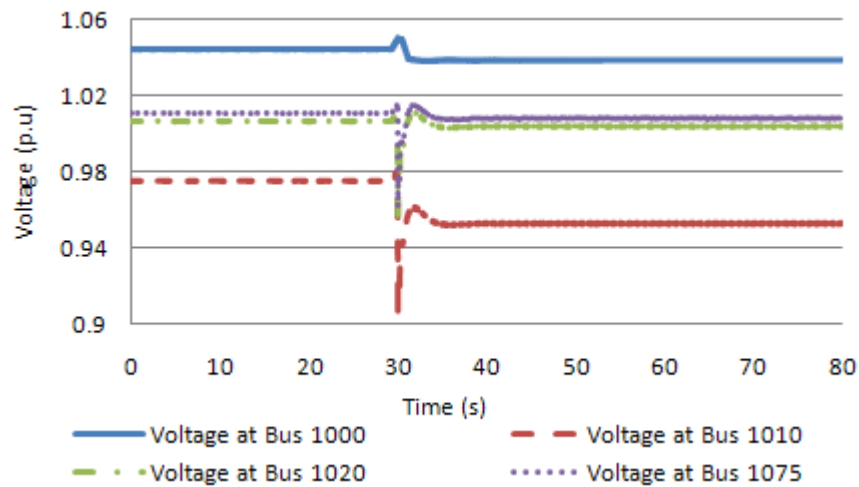


Figure 5.22 Voltage graph in Response Based at Base capacity (fuzzy governor system)

It can be observed from Figure 5.21, that when system encountered Response based disturbance at $t=30s$, the voltage of Bus 1010 located at far distance slightly goes to $0.91p.u$ and recovers to $0.95p.u$ within $0.7s$. In Figure 5.22 voltage of Bus 1010 goes to $0.91p.u$ and recovers to $0.95p.u$ within $0.66s$. Hence, the proposed load shedding scheme also ensures

voltage stability. The power graph of DG with PID based and fuzzy based governor is shown in Figure 5.23.

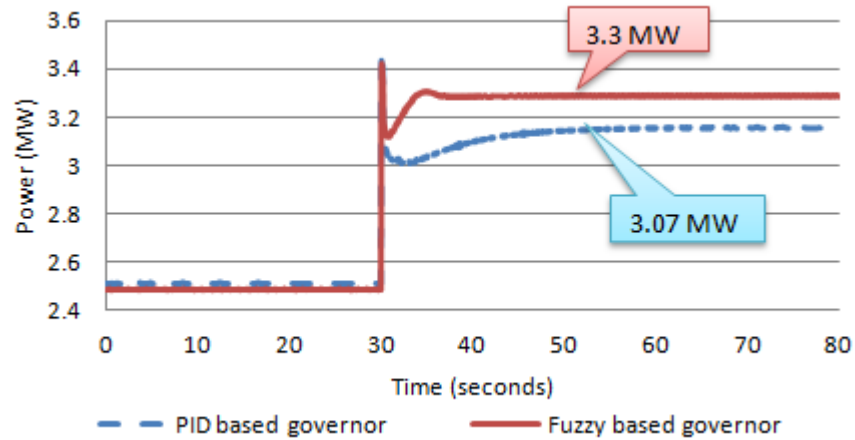


Figure 5.23 Power graph during Response based at base capacity

Figure 5.23 shows that DG with PID based governor supply 0.57 MW load from 1 MW ($2.5 \text{ MW} + 0.57 \text{ MW} = 3.07 \text{ MW}$) and DG with fuzzy based governor supply 0.8 MW load from 1MW ($2.5 \text{ MW} + 0.8 \text{ MW} = 3.3 \text{ MW}$). The load shedding values and breakers tripped during this case are shown in Table 5.4 and the islanded distribution system with breakers tripped is shown in Figure 5.24.

Table 5.4 Load shedding values during response based at base capacity

Governor	Power Supplied	Amount of Load Shed	Power saving	Total no. of Breakers Operated
PID based governor	0.57 MW from 1MW (57 %)	0.43 MW	-	6
Fuzzy based governor	0.8 MW from 1MW (80 %)	0.2 MW	23 %	4

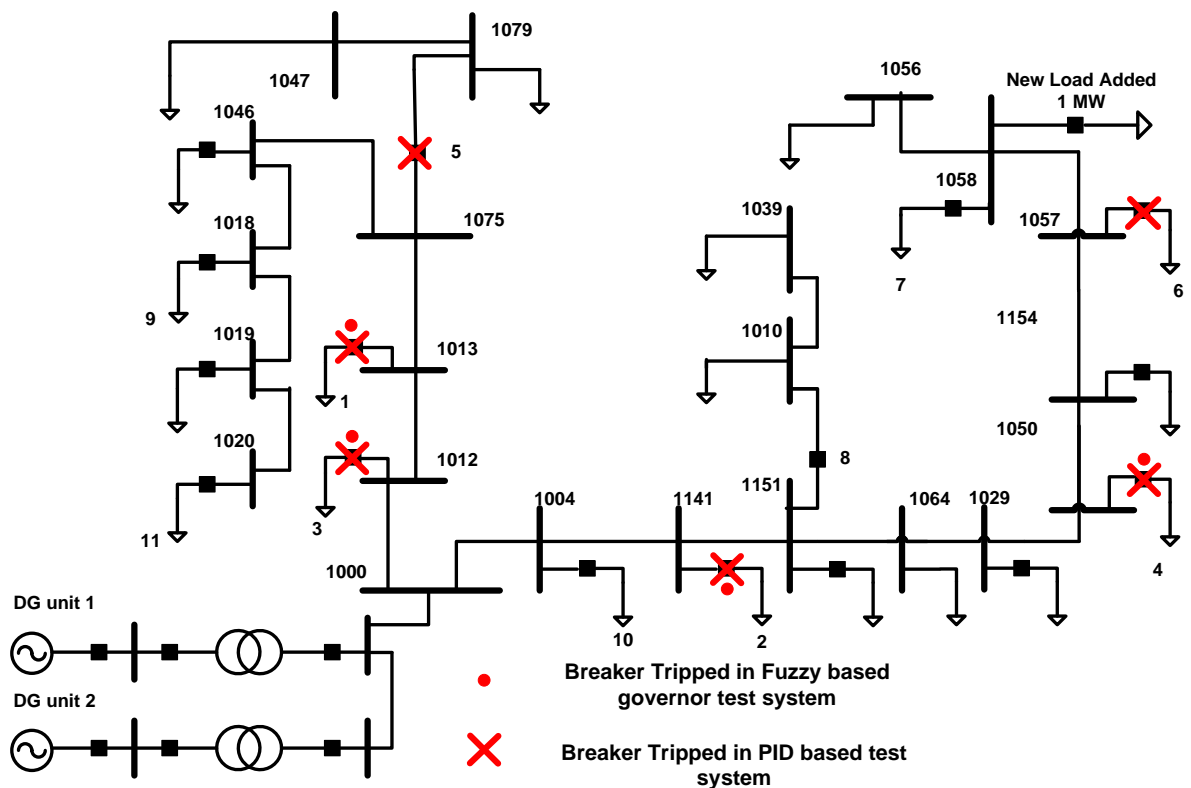


Figure 5.24 Breakers operated during Response based at base capacity

From the Table 5.4, it can be observed that fuzzy based governor enable DG units to utilize 23 % more spinning reserve than PID based governor. FLLSC provides load

shedding for both PID and fuzzy governor based DG. However, fuzzy based governor due to its fast response and robust control enable DG to supply 23 % more load than DG with PID based governor. Thus, a governor plays an important role in fast utilization of DG spinning reserve which results in requiring lesser load to be shed.

5.2.3.2 Response Based at Peak Load Capacity

To simulate Response based condition at peak load capacity (3.6 MW); a load increment of 0.54 MW is applied at bus number 1058 in islanded distribution network. Upon addition of this amount of load, total load becomes $3.6 \text{ MW} + 0.54 \text{ MW} = 4.14 \text{ MW}$. In this case, two DG are already operating at their peak load capacity. Any further increment of load to islanded system severely disturbs its frequency. It may be necessary to shed maximum load to keep the system operating. Response based load shedding is applied at $t=30\text{s}$. The frequency response of DG with PID and fuzzy based governor for this case is shown in Figure 5.25.

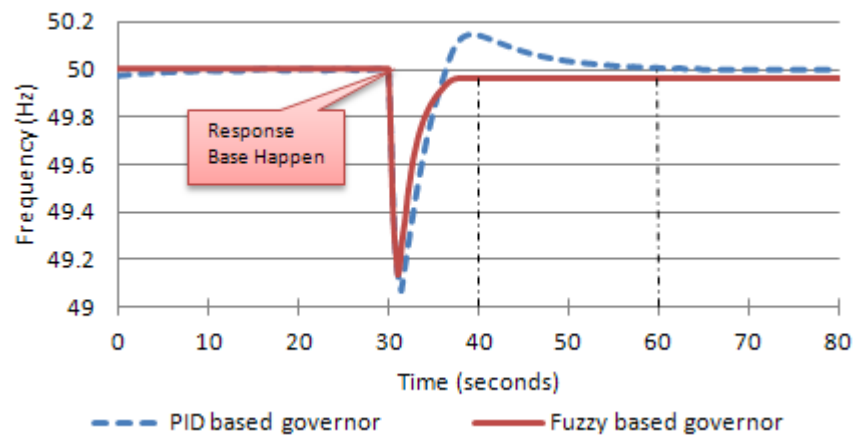


Figure 5.25 Frequency response during Response based at peak capacity

From Figure 5.25, it can be observed that when response base happened at $t=30$ s, the frequency of DG with PID and fuzzy based governor takes 30 s and 10 s to recover to 50 Hz from frequency undershoot of 49.078 Hz and 49.17 Hz respectively. The voltage stability of islanded distribution network for this case is shown in Figure 5.26 and 5.27. Figure 5.26 depicts the voltage magnitude at these buses for this case when system is tested with PID based governor, whereas Figure 5.27 shows the voltage magnitude when system is tested with fuzzy based governor.

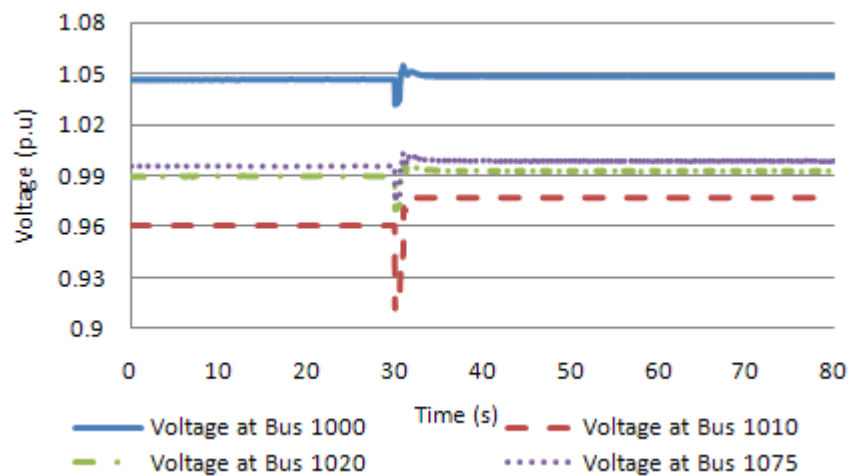


Figure 5.26 Voltage graph in Response Based at Peak capacity (PID governor system)

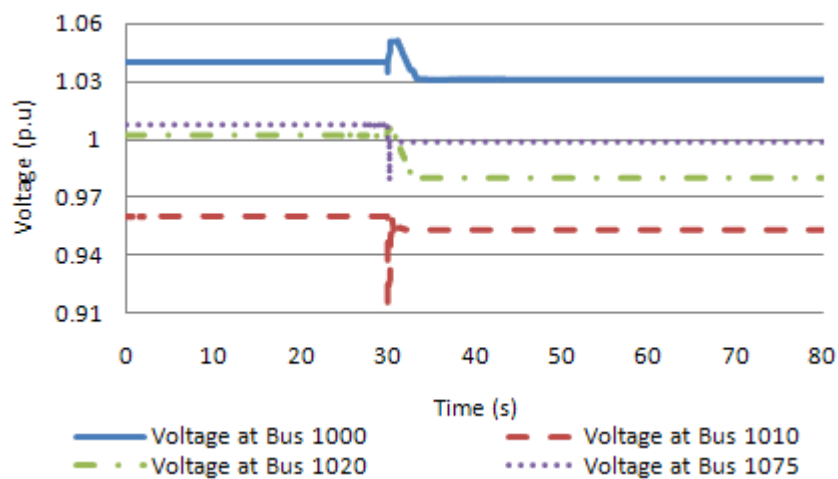


Figure 5.27 Voltage graph in Response Based at Peak capacity (fuzzy governor system)

It can be observed from Figure 5.26 that when system encountered Response based disturbance at $t=30$ s, the voltage of Bus 1010 located at far distance slightly goes to 0.92p.u and recovers to 0.95p.u within 0.57s. In Figure 5.27, the voltage of Bus 1010 goes to 0.92p.u and recovers to 0.95p.u within 0.57s. Hence, proposed load shedding scheme also ensures voltage stability. The power graph of DG with PID based and fuzzy based governor is shown in Figure 5.28.

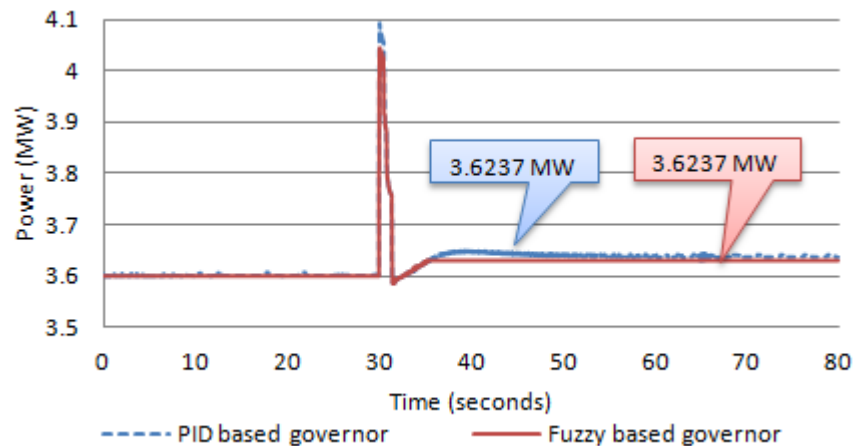


Figure 5.28 Power graph during Response based at peak capacity

Figure 5.28 shows that the power supplied by DG unit with PID and fuzzy based governor remains the same. The load shedding values and total number of breakers tripped during this case are shown in Table 5.5. The islanded distribution system after operation of UFLS scheme is shown in Figure 5.29.

Table 5.5 Load shedding values during response based at peak capacity

Governor	Undershoot	Stabilizing Time	Power Supplied	Amount of Load Shed	Total no. of Breakers Operated
PID based governor	49.078 Hz	30 s	0.0237MW from 0.54MW	0.5163MW	5
Fuzzy based governor	49.17 Hz	10 s	0.0237MW from 0.54MW	0.5163MW	5

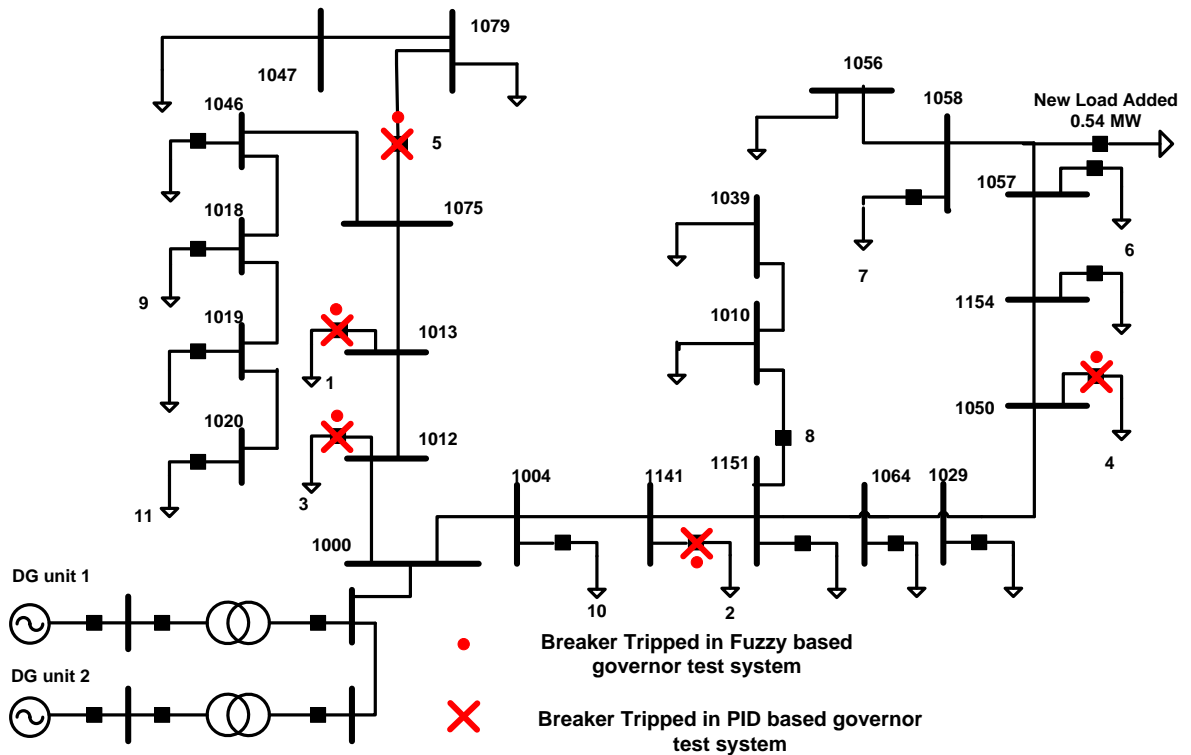


Figure 5.29 Breakers operated during Response based at peak capacity

From Table 5.5, it is noticed that the power supplied by DG units with PID and fuzzy based governor remains the same ($3.6\text{MW} + 0.0237\text{MW} = 3.6237\text{MW}$). However, DG with fuzzy based governor has smaller frequency undershoot and shorter settling time than DG

with PID based governor. LSCM tripped same number of breakers for both governors and the system return to steady state after LSCM suitably shed the required load.

5.2.4 Case IV: Event Based and Response Based Load Shedding

5.2.4.1 Event Based and Response Based at Base Load Capacity

To simulate Event based case at Base load capacity (2.5MW), one of the DG units is tripped-off from islanded distribution system and Response base case is simulated in it by applying a load increment of 0.6 MW. Event based load shedding is applied first followed by Response based load shedding. Event based load shedding scheme is applied at $t = 30$ s and Response based load shedding is applied at $t = 70$ s. The frequency response and power graph of DG with PID and fuzzy based governor for this case is shown in Figure 5.30-5.31.

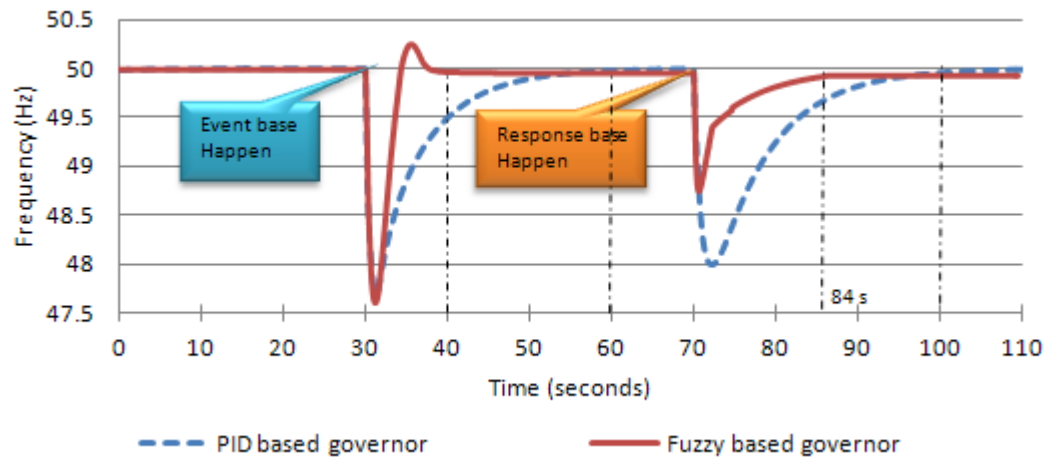


Figure 5.30 Frequency response for Event and Response based at base load capacity

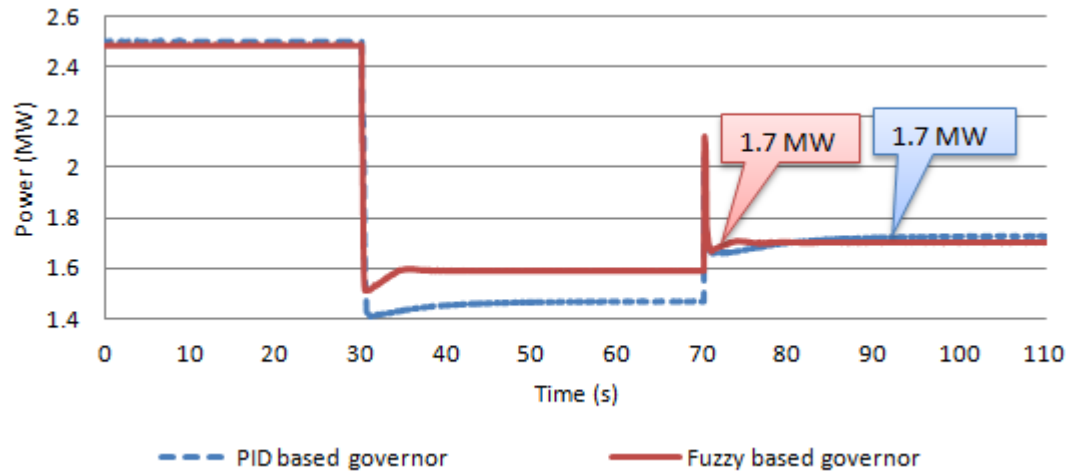


Figure 5.31 Power graph for Event and Response based at base load capacity

From Figure 5.30, it can be observed that PID based governor recovers the DG frequency to 50 Hz after 30s for each case whereas, fuzzy based governor recovers the DG frequency to 50 Hz after 10s and 14s for Event and Response based case respectively. The DG with PID based governor has undershoot of 47.7 Hz (for Event based) and 48 Hz (for Response based) respectively. Whereas, DG with fuzzy based governor has undershoot of 47.6 Hz (for Event based) and 48.74 Hz (for Response based) respectively. The voltage stability of islanded distribution network for this case is shown in Figure 5.32-5.33.

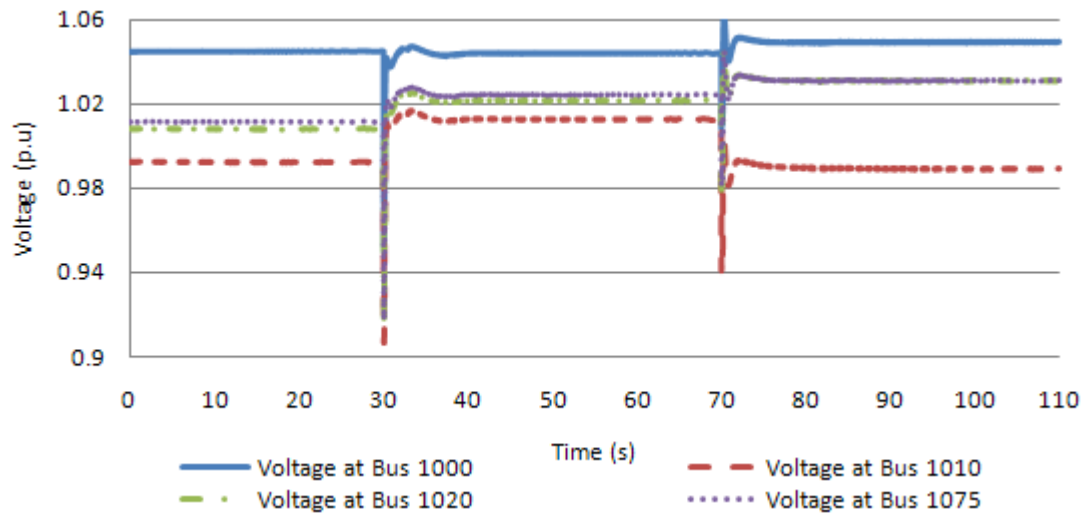


Figure 5.32 Voltage in Event and Response Based at Base capacity (PID governor)

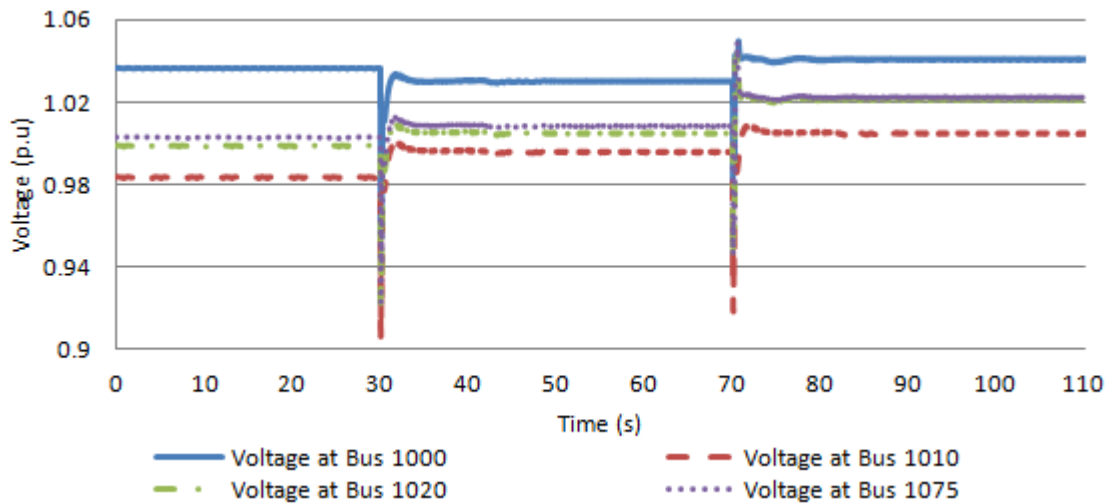


Figure 5.33 Voltage in Event and Response Based at Base capacity (fuzzy governor)

It can be observed from Figure 5.32 that when system encountered Event and Response based disturbance at $t=30s$ and $t=70s$ respectively, the voltage of Bus 1010 located at far distance slightly goes to $0.907p.u$ and $0.947p.u$ and recovers to $0.95p.u$ within $0.15 s$ and $0.17s$ respectively. In Figure 5.33 the voltage of Bus 1010 goes to $0.905p.u$ and $0.917p.u$

and recovers to 0.95p.u within 0.16 s and 0.24 s respectively. Hence, the proposed load shedding scheme ensures voltage stability. The distribution system after operation of UFLS scheme is shown in Figure 5.34.

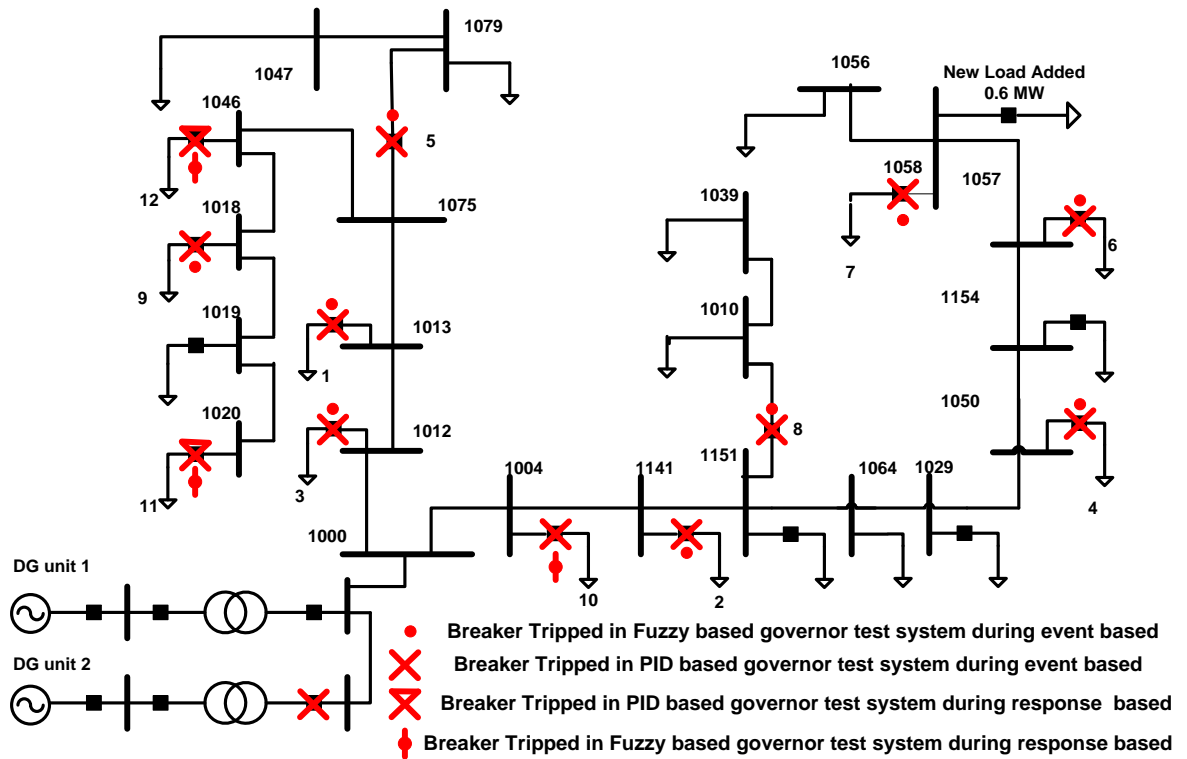


Figure 5.34 Breakers operated during Event and Response based at base capacity

The load shedding values and breakers tripped during this case are shown in Table 5.6

Table 5.6 Load shedding values in Event and Response based at base capacity

Governor	Power Supplied	Amount of Load Shed	Breakers tripped in Event base	Power Supplied	Amount of Load Shed	Breakers tripped in Response base
PID based governor	1.47MW (73.5%)	1.03MW	10	0.23MW from 0.6MW	0.37MW	2
Fuzzy based governor	1.6MW (80%)	0.9MW	9	0.1MW from 0.6MW	0.5MW	3

From Table 5.5, it can be observed that during Event based case, DG with PID based governor supply 73.5 % (1.47 MW) load of its capacity. Whereas, DG with fuzzy based governor supply 80 % (1.6 MW) load of its capacity. Thus, fuzzy based governor enables the DG unit to utilize 6.5 % more spinning reserve of generating system than PID based governor. The total number of RCB breakers operated in fuzzy based governor is 9 and in PID based governor is 10.

In Response based case, 0.6 MW load disturbance is applied. The DG unit with PID based governor supplies 0.23 MW load and 0.37 MW load was shed by LSCM as shown in Table 5.5. Thus, total load supplied by DG unit with PID based governor increased from 73.5 % (1.47 MW) to 85 % (1.7 MW). The DG unit with fuzzy based governor supplies 0.1 MW load and 0.5 MW of load was shed by LSCM. The total load supplied by DG unit with fuzzy based governor increased from 80 % (1.6 MW) to 85 % (1.7 MW). It seems that PID based governor enable DG to supply more power in Response based load shedding case than DG with fuzzy based governor. However, it is not true. Since, after Event based load shedding, DG with fuzzy based governor was more loaded (1.6 MW) than DG with PID based governor (1.47 MW); thus, when Response based load shedding occurs, DG with

fuzzy based governor supply less power as compared to DG with PID based governor. However, overall power supplied by DG with fuzzy based governor is similar to DG with PID based governors as shown above in Figure 5.31.

5.2.4.2 Event Based and Response Based at Peak Load Capacity

To simulate Event based case at peak load capacity (3.6MW), one of the DG units is tripped-off from islanded distribution system and Response base case is simulated in it by applying a load increment of 0.6 MW. Event based load shedding scheme is applied at $t = 30$ s and Response based load shedding is applied at $t = 70$ s. In this case, FLLSC by measuring frequency, df/dt and RCB status will determine, whether system encountered Event based or Response based load disturbance. The frequency response and power graph of DG with PID and fuzzy based governor for this case is shown in Figure 5.35-5.36.

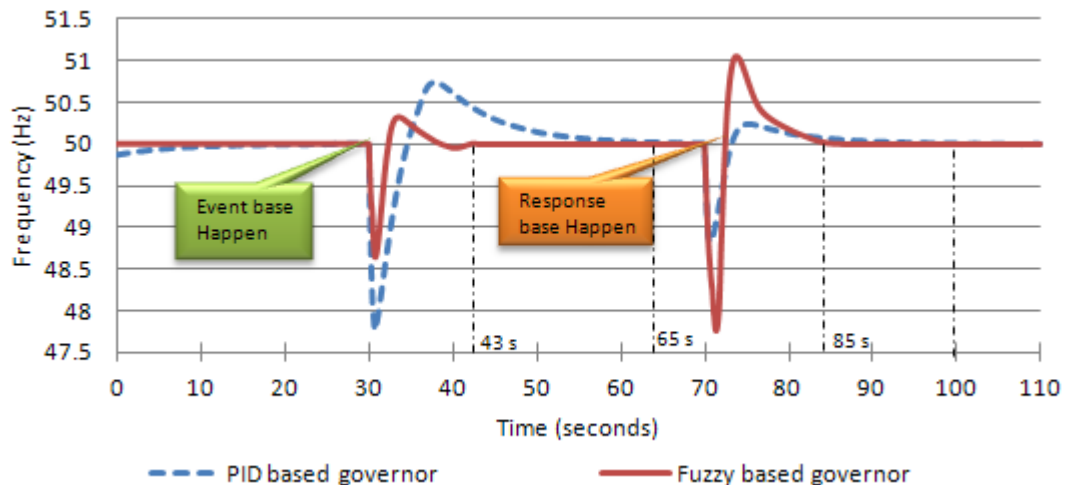


Figure 5.35 Frequency response for Event and Response based at peak load capacity

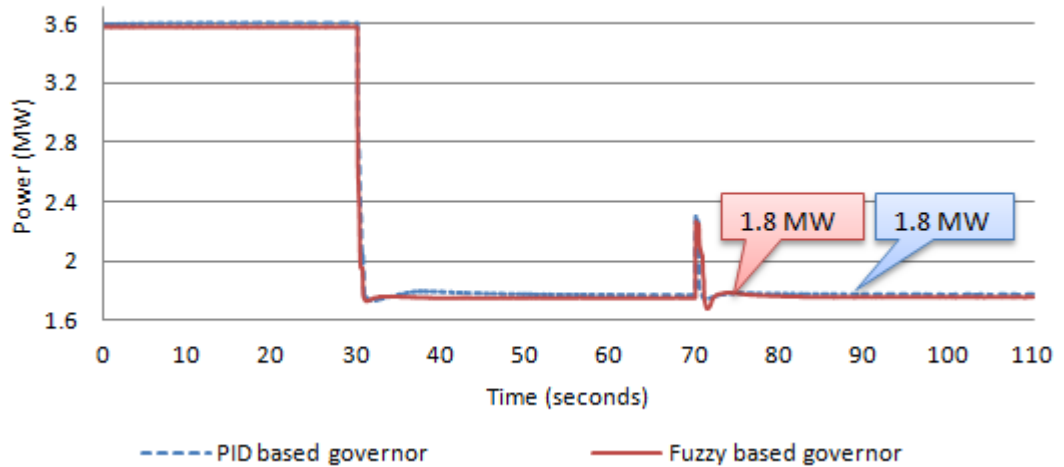


Figure 5.36 Power graph for Event and Response based at peak load capacity

From Figure 5.35, it can be observed that PID based governor recovers the DG frequency to 50 Hz after 35s and 30s for Event and Response based case respectively whereas, fuzzy based governor recovers the DG frequency to 50 Hz after 13s and 15s for Event and Response based case respectively. The DG with PID based governor has undershoot of 47.75 Hz (for Event based) and 48.8 Hz (for Response based) respectively. Whereas, DG with fuzzy based governor has undershoot of 48.68 Hz (for Event based) and 47.78 Hz (for Response based) respectively. The voltage stability of islanded distribution network for this case is shown in Figure 5.37-5.38.

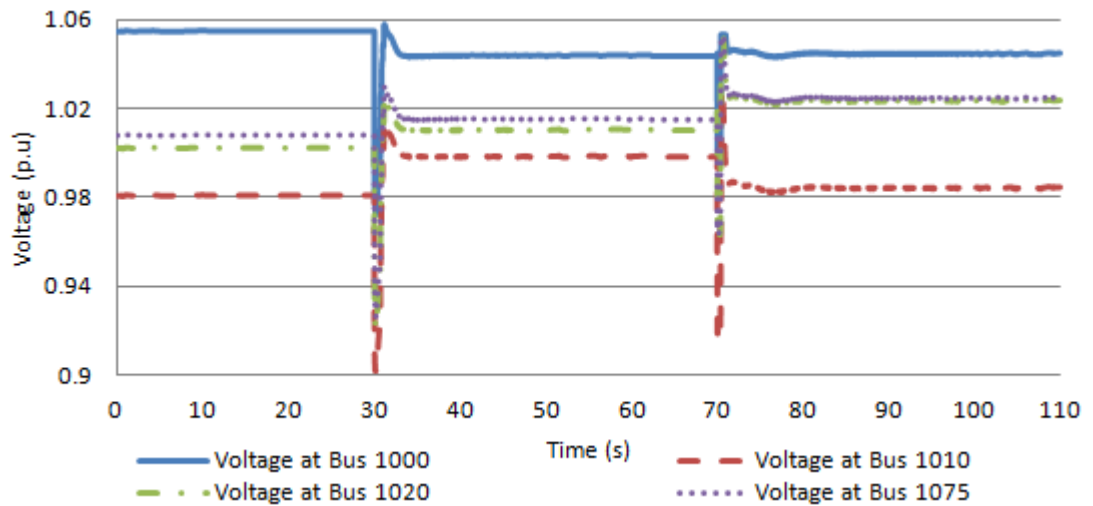


Figure 5.37 Voltage in Event and Response Based at Peak capacity (PID governor)

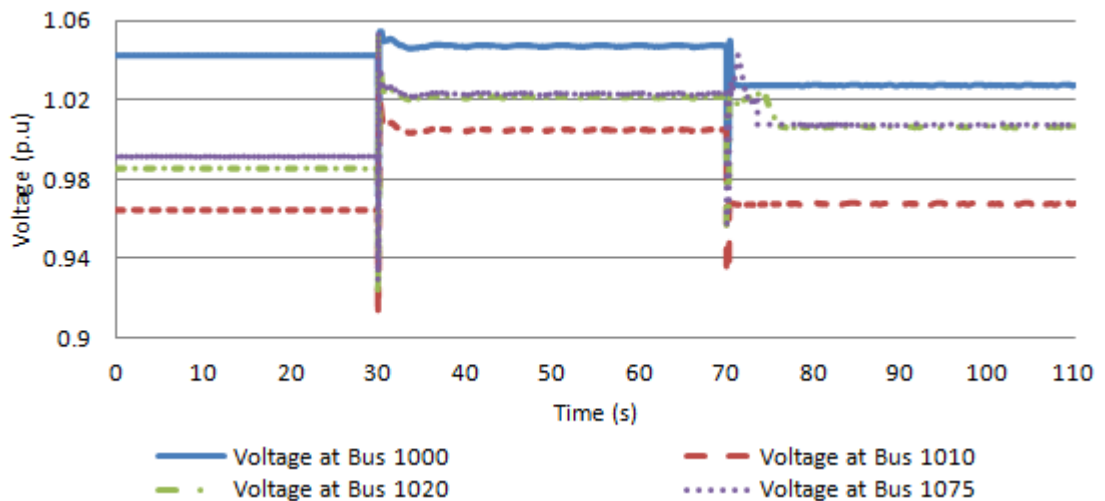


Figure 5.38 Voltage in Event and Response Based at Peak capacity (fuzzy governor)

It can be observed from Figure 5.37 that when system encountered Event and Response based disturbance at $t=30s$ and $t=70s$ respectively, the voltage of Bus 1010 located at most far distance slightly goes to 0.9017 p.u and 0.94p.u and recovers to 0.95 p.u within 0.74s and 0.45s respectively. In Figure 5.38 the voltage of Bus 1010 goes to 0.908p.u and 0.92

Table 5.7 Load shedding values in Event and Response based at peak capacity

Governor	Power Supplied	Amount of Load Shed	Breakers tripped in Event base	Power Supplied	Amount of Load Shed	Breakers tripped in Response base
PID based governor	1.8MW (90%)	1.8MW	11	0MW from 0.6MW	0.6MW	3
Fuzzy based governor	1.8MW (90%)	1.8MW	11	0MW from 0.6MW	0.6MW	3

From Table 5.7 it can be observed that during Event base case, DG with fuzzy and PID based governor supply 90 % (1.8 MW) load of its capacity. During Response based load shedding, FLLSC estimates optimum load shedding value and sends this value to LSCM. The LSCM tripped 3 more RCB to stabilize the DG frequency. It is noticed that during Response based case, LSCM shed all 0.6 MW load to stabilize the frequency enabling DG unit to operate continuously. The DG units with fuzzy based governor and PID based governor maintain the previous supply up to of 90 % (1.8 MW). Since, in this case the DG units were already operating at their peak capacity. Hence, any increase in load is to be fully shed in order to stabilize the DG frequency and keep the DG unit operating.

5.3 Overall Observation

From the conducted tests for LFC, it can be concluded that the proposed fuzzy based governor provides better frequency control during large load variation with smaller overshoot, undershoot and shorter settling time than PID based governor. The proposed fuzzy based governor enables DG units to supply power at 25% load variation while

keeping frequency within acceptable limits. Whereas, the DG with PID based governor fail to provide supply power at 20% load variation.

From the conducted tests for UFLS scheme, it can be clearly seen that the proposed fuzzy based UFLS scheme sheds the optimum load according to disturbance magnitude. The fuzzy logic load shedding controller (FLLSC) successfully distinguishes between event based and response based cases and intelligently estimates power imbalance to shed the load. FLLSC send this value to load shed controller module (LSCM) for shedding the estimated load in one step. The proposed method can prevent the frequency drop by shedding optimal load in order to maintain the system stability. In one glance, this algorithm can improve and enhance the system frequency response.

From the UFLS conducted tests, it can also be concluded that governor plays an important role in fast utilization of spinning reserve, which results in requiring lesser load to be shed in UFLS scheme. From the results of UFLS scheme, it is observed that DG with fuzzy based governor can supply more power and require lesser load to be shed than DG with PID based governor. This is due to robust control and fast utilization of DG spinning reserve by fuzzy based governor.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Summary

This thesis has presented the implementation of fuzzy logic control as a governor for load frequency control of mini hydro type DG. The fuzzy based governor has been implemented in PSCAD through C-program. Response of fuzzy based governor when compared with PID based governor has shown that fuzzy based governor provides robust control, having smaller frequency undershoot, overshoot and settling time than PID based governor. Fuzzy based governor enable DG unit to ensure continuous supply to distribution network at 25% load variation whereas, with PID based governor DG unit fails to continue supply at 20% load variation.

Apart from this, under frequency load shedding (UFLS) schemes are required to prevent frequency decline in the DG system due to over loading in the system. Conventional UFLS schemes are not suitable for islanding mode of operation, since these UFLS schemes mostly applicable to transmission network having high inertia and different system parameter and are successful for normal operation. However, in islanding operation frequency and voltage changes severely and require adaptive and intelligent UFLS schemes. This thesis proposed an intelligent fuzzy based UFLS scheme, to improve system stability and security by enhancing frequency response of the system on occurrence of contingency in power system.

The proposed UFLS scheme considers both event-based and response based cases. Developed UFLS scheme provide a fast decision to prevent frequency decline in the system. This UFLS method maximizes system benefit and stability, minimizes load curtailment and provides a better response of the system frequency and voltage. Furthermore, by prioritizing the load in three categories; non-vital, semi-vital and vital, a better load shedding can be obtained. The effectiveness and robustness of this scheme has been investigated on different cases from base load to peak load. Fuzzy logic load shedding controller (FLLSC) successfully estimates the optimum amount of power imbalance and intelligently distinguishes between event and response base cases. Hence, by combining the governor and UFLS scheme based on fuzzy, both Event based and Response based cases can be addressed successfully.

The study also shows that the type of governor plays an important role in robust frequency control and in fast utilization of DG spinning reserve. The amount of load to be shed greatly depends on, how fast governor can utilize its DG spinning reserve. If governor utilizes its spinning reserve quickly, the amount of load to be shed will be smaller and vice versa. In order to test the effect of governor, proposed UFLS scheme is tested with PID based governor and fuzzy based governor. It has been observed that proposed UFLS scheme with fuzzy based governor sheds lesser loads than PID based governor. Thus, fuzzy based governor provides robust frequency control and quickly utilizes DG spinning reserve, enables DG to supply more power. Hence, a DG with fuzzy based governor requires lesser load to be shed during event base and response base load disturbances.

6.2 Future Work

The proposed under frequency load shedding scheme (UFLS) can be improved by considering the following recommendations:

- (1) The load shedding scheme can be further improved by considering load restoration techniques.
- (2) Reliability of the system can be further increased by considering protection devices such as relays along with UFLS scheme in order to distinguish the faults and load disturbance in the system.
- (3) The proposed UFLS algorithm can be further improved by considering combination of fixed load priority and random load priority. The non-vital loads can be shed with random load priority and semi-vital and vital loads on fixed load priority. This may result in shedding of more optimum loads and prevent UFLS scheme to shed more loads than required due to fixed load priority.
- (4) The system can also consider state estimation method to reduce load measuring devices in the distribution network.

REFERENCES

- Anderson, P. M., & Mirheydar, M. (1992). An adaptive method for setting underfrequency load shedding relays. *IEEE Transactions on Power Systems*, 7(2), 647-655.
- Atherton, D. P., & Majhi, S. (1999). *Limitations of PID controllers*. Paper presented at the Proceedings of the American Control Conference
- Barker, P. P., & De Mello, R. W. (2000). *Determining the impact of distributed generation on power systems. I. Radial distribution systems*. Paper presented at the IEEE Power Engineering Society Summer Meeting, .
- Borbely, A., Kreider, J., . (2001). *Distributed Generation: the power paradigm for the new millennium*. CRC Press.
- Culberg, J. L., Negnevitsky, M., & Muttaqi, K. M. Hydro-turbine governor control: theory, techniques and limitations in Proceedings of AUPEC (2006) 1-5.
- Delfino, B., Massucco, S., Morini, A., Scalera, P., & Silvestro, F. (2001). *Implementation and comparison of different under frequency load-shedding schemes*. Paper presented at the Power Engineering Society Summer Meeting, 2001.
- Ding, Z., Cartes, D. A., & Srivastava, S. (2006). *New load shedding scheme for islanded power systems*. Paper presented at the IEEE/SMC International Conference on System of Systems Engineering, 2006
- Dola, H. M., & Chowdhury, B. H. (2006). *Intentional islanding and adaptive load shedding to avoid cascading outages*. Paper presented at the Power Engineering Society General Meeting, 2006. IEEE.
- Doolla, S., & Bhatti, T. S. (2006). Load Frequency Control of an Isolated Small-Hydro Power Plant With Reduced Dump Load. *IEEE Transactions on Power Systems*, 21(4), 1912-1919.
- Hadi, S. (1999). *Power System Analysis*. McGraw-Hill.

- Hanmandlu, M., & Goyal, H. (2008). Proposing a new advanced control technique for micro hydro power plants. [doi: DOI: 10.1016/j.ijepes.2007.07.010]. *International Journal of Electrical Power & Energy Systems*, 30(4), 272-282.
- Hanmandlu, M., Goyal, H., & Kothari, D. P. (2006, 12-15 Dec. 2006). *An Advanced Control Scheme for Micro Hydro Power Plants*. Paper presented at the International Conference on Power Electronics, Drives and Energy Systems.
- Hashim, H., & Ho, W. S. (2011). Renewable energy policies and initiatives for a sustainable energy future in Malaysia. *Renewable and Sustainable Energy Reviews*, 15(9), 4780-4787.
- Henderson, D. (1998). An advanced electronic load governor for control of micro hydroelectric generation. *IEEE Transactions on Energy Conversion*, 13(3), 300-304.
- Hirodantis, S., Li, H., & Crossley, P. A. (2009). *Load shedding in a distribution network*. Paper presented at the International Conference on Sustainable Power Generation and Supply, 2009.
- Hydraulic turbine and turbine control models for system dynamic studies. (1992). *IEEE Transactions on Power Systems*, 7(1), 167-179.
- IEEE Guide for Abnormal Frequency Protection for Power Generating Plants. (1987). *ANSI/IEEE Std C37.106-1987*, 0_1.
- IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration. (2007). *IEEE Std C37.117-2007*, c1-43.
- IEEE Recommended Practice for Excitation System Models for Power System Stability Studies. (2006). *IEEE Std 421.5-2005 (Revision of IEEE Std 421.5-1992)*, 0_1-85.
- IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems. (2000). *IEEE Std 929-2000*, i.
- IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems. (2003). *IEEE Std 1547-2003*, 0_1-16.

- Jones, J. R., & Kirkland, W. D. (1988). Computer algorithm for selection of frequency relays for load shedding. *Computer Applications in Power, IEEE*, 1(1), 21-25.
- Khodabakhshian, A., & Golbon, N. (2005). *Robust load frequency controller design for hydro power systems*. Paper presented at the Proceedings of IEEE Conference on Control Applications.
- Khodabakhshian, A., & Hooshmand, R. (2010). A new PID controller design for automatic generation control of hydro power systems. [doi: DOI: 10.1016/j.ijepes.2009.11.006]. *International Journal of Electrical Power & Energy Systems*, 32(5), 375-382.
- Kishor, N., Saini, R. P., & Singh, S. P. (2007). A review on hydropower plant models and control. [doi: DOI: 10.1016/j.rser.2005.06.003]. *Renewable and Sustainable Energy Reviews*, 11(5), 776-796.
- Kundur, P. (1994). *Power System Stability and Control McGraw-Hill*.
- Lukic, M., Kuzle, I., & Tesnjak, S. (1998). *An adaptive approach to setting underfrequency load shedding relays for an isolated power system with private generation*. Paper presented at the 9th Mediterranean Electrotechnical Conference, MELECON
- Mahat, P., Zhe, C., & Bak-Jensen, B. (2010). Underfrequency Load Shedding for an Islanded Distribution System With Distributed Generators. *IEEE Transactions on Power Delivery*, 25(2), 911-918.
- Mohd Zin, A. A., Mohd Hafiz, H., & Aziz, M. S. *A review of under-frequency load shedding scheme on TNB system*. Paper presented at the National Proceedings. Power and Energy Conference, PECon 2004.
- Mohd Zin, A. A., Mohd Hafiz, H., & Aziz, M. S. (2004, 29-30 Nov. 2004). *A review of under-frequency load shedding scheme on TNB system*. Paper presented at the Power and Energy Conference, 2004. PECon 2004. Proceedings. National.
- Ozbay, E., & Gencoglu, M. T. (2010). Load frequency control for small hydro power plants using adaptive fuzzy controller. *in Proc. SMC*, 4217-4223.

- Pasand, M. S., & Seyedi, H. (2007). *New Centralized Adaptive Under Frequency Load Shedding Algorithms*. Paper presented at the Large Engineering Systems Conference on Power Engineering, .
- Poulin, E., & Pomerleau, A. (1997). Unified PID design method based on a maximum peak resonance specification. *IEE Proceedings on Control Theory and Applications*, 144(6), 566-574.
- Puchala, k., Belmen, R., & Exarchakos, K. h., A. Distributed Generation and the Grid integration issues. *Imperial College London, UK, EUSUSTEL, Work Package 3*
- Ranjitkar, G., Jinxing, H., & Tung, T. (2006, 10-12 May 2006). *Application of Micro-Hydropower Technology for Remote Regions*. Paper presented at the IEEE EIC Climate Change Technology
- Report, I. C. (1973). Dynamic Models for Steam and Hydro Turbines in Power System Studies. *IEEE Transactions on Power Apparatus and Systems*, PAS-92(6), 1904-1915.
- Salhi, I., Chennani, M., Doubabi, S., & Ezziani, N. (2008). *Modeling and regulation of a micro hydroelectric power plant*. Paper presented at the IEEE International Symposium on Industrial Electronics.
- Salhi, I., Doubabi, S., & Essounbouli, N. (2010a). *Design and simulation of fuzzy controller and supervisor for a micro-hydro power plant*. Paper presented at the 18th Mediterranean Conference on Control & Automation (MED).
- Salhi, I., Doubabi, S., & Essounbouli, N. (2010b). *Fuzzy control of micro hydro power plants*. Paper presented at the 5th IET International Conference on Power Electronics, Machines and Drives
- Salhi, I., Doubabi, S., Essounbouli, N., & Hamzaoui, A. (2010). Application of multi-model control with fuzzy switching to a micro hydro-electrical power plant. [doi: DOI: 10.1016/j.renene.2010.02.008]. *Renewable Energy*, 35(9), 2071-2079.
- Seyedi, H., & Sanaye-Pasand, M. (2009). New centralised adaptive load-shedding algorithms to mitigate power system blackouts. *Generation, Transmission & Distribution, IET*, 3(1), 99-114.

- Shokooh, S., Khandelwal, T., Shokooh, F., Tastet, J., & Dai, J. J. (2005). Intelligent Load Shedding Need for a Fast and Optimal Solution. *IEE PCIC Europe*.
- Singh, S., & Rattan, K. S. (2003, 23-25 Sept. 2003). *Implementation of a fuzzy logic controller on an FPGA for a DC motor*. Paper presented at the Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Technology Conference, 2003. Proceedings.
- Terzija, V. V., & Koglin, H. J. (2002). Adaptive underfrequency load shedding integrated with a frequency estimation numerical algorithm. *Generation, Transmission and Distribution, IEE Proceedings-*, 149(6), 713-718.
- Thompson, J. G., & Fox, B. (1994). Adaptive load shedding for isolated power systems. *Generation, Transmission and Distribution, IEE Proceedings-*, 141(5), 491-496.
- Vijay Vittal, H. Y., Chen-Ching Liu, Juhwan Jung, Massoud Admin, Ram Adapa, . (2002). *An Intelligent Adaptive Load Shedding Scheme*. Paper presented at the Power Systems Computation Conference (PSCC), Seville, Spain.
- Walling, R. A., & Miller, N. W. (2002). *Distributed generation islanding-implications on power system dynamic performance*. Paper presented at the Power Engineering Society Summer Meeting, 2002 IEEE.