UNDERVOLTAGE LOAD SHEDDING IN ISLANDED MICROGRIDS

A report submitted in partial fulfillment of the requirements

for the degree of

BACHELOR OF TECHNOLOGY

MASTER OF TECHNOLOGY

submitted by

G Ashish Raja

EE11B112

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY MADRAS

MAY 2017

THESIS CERTIFICATE

This is to certify that the thesis titled **UNDERVOLTAGE LOAD SHEDDING IN ISLANDED MICROGRIDS**, submitted by **G Ashish Raja EE11B112**, to the Indian Institute of Technology, Madras, for the award of the degree of **Bachelor of Technology and Master of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr. K Shanti Swarup
Research Guide
Professor
Dept. of Electrical Engineering
IIT-Madras, 600036

Place: Chennai
Date:

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to Dr. K Shanti Swarup , my project guide, for his guidance, support and patience throughout the project. His enormous knowledge and research enthusiasm is incomparable and it made a great impact on me. He has been a constant source of encouragement and motivation and I consider myself fortunate to work under his guidance. I would also like to thank the Head of the Electrical Engineering Department for giving me the opportunity to work under my guide, Dr. K Shanti Swarup, I take this opportunity to express sincere gratitude to all of the IIT Madras faculty members for their sharing expertise, and valuable guidance and encouragement extended to me.. My sincere thanks to my friends and colleagues for their help regardless of time. I am indebted to my parents for their blessings and encouragement.

ABSTRACT

KEYWORDS: Islanded Micro grid ,Distributed Control ,Under voltage Load Shedding, Adaptive Load Shedding, Voltage Collapse Delayed Voltage recovery

In the islanded operating condition, the micro-grid has to maintain the power balance independently of a main grid. Because of the specific characteristics of the microgrid, such as the resistive lines and the high degree of power-electronically interfaced generators, new power control methods for the generators have been introduced. Because of the small size of the micro grid and the high share of renewables with an intermittent character, new means of flexibility in power balancing are required to ensure stable operation. Therefore, a novel active load control strategy is presented here . A Load Shedding plan against long haul voltage instability is proposed. It utilizes an arrangement of distributed controllers, each observing transmission voltages in a zone and controlling a group of related loads. Each controller acts in closed-loop, shedding amounts that vary in magnitude and time according to the evolution of its monitored voltage. The Load shedding plan considers both voltage collapse and delayed voltage recovery .The whole system can operate without information exchange between controllers, the latter being implicitly coordinated through network voltages. The operation, design and robustness features are illustrated through simulations of a real system.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Microgrid-an introduction

Micro grid concept as a quasi-power system is introduced because of various reasons like environmental pollution, economical issues, depletion of fossil fuel resources, market . A cluster of loads and micro sources operating as a single controllable system that provides both power and heat to its local area is defined as micro grid (MG) . Wind turbine, solar cell, fuel cell, micro turbine are the examples of MG sources with clean energies . Depending on source type, it is connected via synchronous generator, induction generator or power electronic converter/inverter as interface. They are located in distribution voltage level and near to costumer. This vicinity brings with itself the advantages such as losses reduction and efficient increase. Moreover, the ability of operation in both grid- connected and isolated modes increases reliability .Despite of MG advantages there are several problems like the absence of standard about power quality and voltage and frequency profiles, difficulty of control and protection plans. Normally, a MG is connected to main grid and exchanges power with it. It is expected to DGs generate pre-specified power for example minimize power import from the grid. It is different from one system to another system. In this mode, grid serves as backup and eliminates unbalancing. But islanding either by planned or unplanned events separates main grid. Such events are described in. MG is disconnected from distribution grid via breaker by point of common coupling (PCC). In transit from grid-connected mode to islanded mode, MGs depend on their previous conditions such as amount of interchanged power. They usually absorb power from grid, in the grid-connected mode. As a result, unbalancing power is created in islanded mode. Similar to conventional systems, isolated MGs can face different events such as tripping generator, unbalancing between generation and consumption, power quality issues. So, stable operation needs proper controllers. Various control loops of local, global, secondary and emergency are used to keep MG. The role of controllers is to maintain system integrity and restore the normal operation subjected to a disturbances but each controller could response to some disturbances . Small disturbances do not need critical actions but large disturbances need emergency control to prevent blackout system. A typical micro grid is shown in fig 1.1.

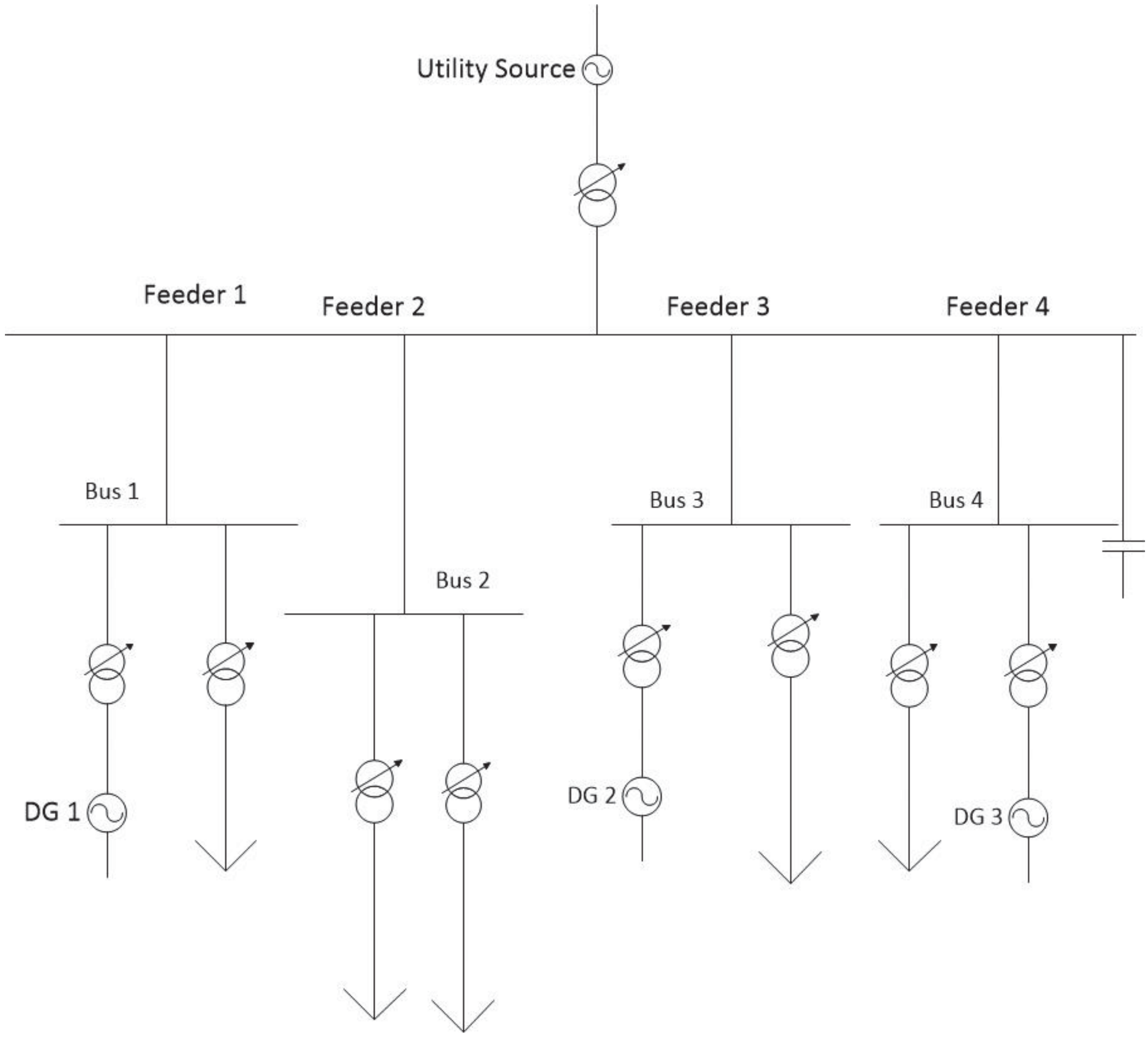

Figure 1.1: A Micrgrid

1.2 Islanded microgrids

The MG operates autonomously, in a similar way to physical islands, when the disconnection from the upstream MV network occurs, it is called islanded mode of operation. The need of reducing emissions in the electricity generation field, recent technological developments in the micro generation domain, and electricity business restructuring are the main factors responsible for the growing interest in the use of micro generation. In fact, the connection of small generation units the micro sources (MS), with power ratings less than a few tens of kilowattsâĂŤto low voltage (LV) networks potentially increases reliability to final consumers and brings additional benefits for global system operation and planning, namely, regarding investment reduction for future grid reinforcement and expansion. In this context, a Micro Grid (MG) can be defined as an LV network (e.g., a small urban area, a shopping centre, or an industrial park) plus its loads and several small modular generation systems connected to it, providing both power and heat to local loads. A key advantage is that the micro grid appears to the power network as a single controllable unit, enabling it to deliver the cost benefits of large units. Furthermore, micro grids can enhance local reliability, reduce feeder losses, provide reactive power and local voltage support, remove transmission and distribution bottlenecks, increase efficiency through combined heat and power (CHP), and provide uninterruptible power supply functions. The increased amount of small-scale power sources that are not directly online requires the development of converter-based micro grids. Hence, the micro grid control focuses on the control of these converters Islanded mode can occur in case of special situations such as grid faults or outage of the bulk supply . This offers potential improvement of efficiency, reliability, quality and costs. In Canada, for example, some projects are running for intentional islanding to increase the reliability of the power supply in rural feeders and for maintenance without supply interruption. Another reason for the islanded micro grid operation is to realize sustainable human development. According to the World BankâĂŹs 2010 development report, 1.6 billion people in developing countries do not have access to electricity. The most important reason of this insufficient distribution of electrical sources is the extensive investment to install large grid-connected power lines across large distances for expansion of the electricity supply to a few people. Islanded micro grid projects provide great opportunities in these cases, with an example in the Sundarbans Islands region in India. Also, micro grids give opportunities in the field of the smart grids as smart grids are expected to emerge in an evolutionary path, firstly coexisting with the existing grid as smart micro grids. Most existing papers on intentional islanding operation of converter fed micro grids propose to operate the converters as voltage sources as show in fig 1.2. . Like in a typical UPS, the converters regulate their output voltage magnitude while a frequency generator sets the frequency at 60 Hz. Therefore, power electronic interfaces (dc/ac or ac/dc/ac) are required. Inverter control is thus the main concern in MG operation.

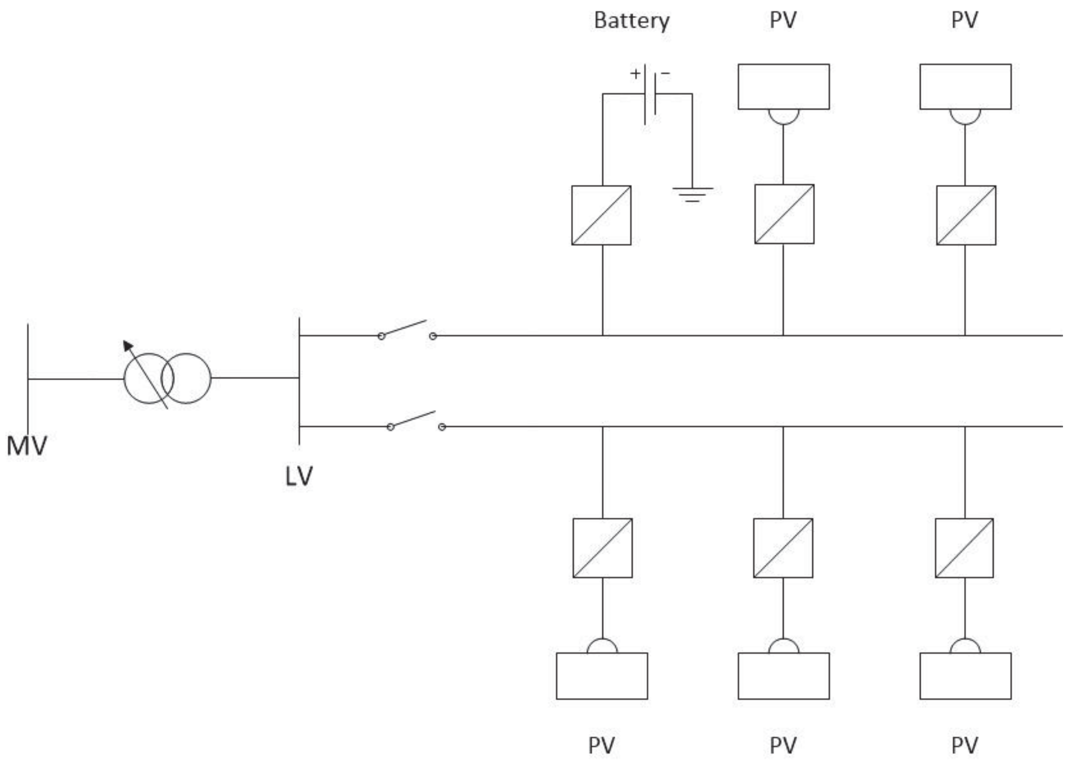

Figure 1.2: A Micrgrid with power converter interfaced source

1.3 Under voltage in islanded microgrids

Interconnection of micro grids is a practical way to achieve higher utilisation of renewable energy, reduce transmission losses, lower infrastructure capital investment, and achieve higher reliability of electricity supply. Experimental micro grids have been developed to test the basic ideas Energy sources in micro grids are likely to be renewable resources interconnected via voltage source converters (VSC). Most VSCs are controlled to output a set voltage magnitude and phase. This is in contrast to synchronous machine based grid operation where the voltage magnitude interaction between the generation and load dynamics. If the VSC output voltage magnitude and angle are not controlled the system operation will result in unplanned generation levels and voltage profile in micro grids. There might be large numbers of unbalanced and nonlinear loads in the three-phase micro grid such as single-phase loads, rectifier loads, etc. Unfortunately, power quality of the islanded micro grid can be deteriorated under unbalanced and nonlinear loads since it lacks of the voltage and frequency support from the utility. Unbalanced and harmonic-distorted voltage can cause severe problems on equipment such as vibration, over-voltage, over-heat, etc. In an Islanded micro grid voltage sag is caused either due to fault in the customer facility or due to starting of large motor load (Induction). The voltage sag causes high inrush current in order to provide rated power, there by causes damage to equipments. Under voltage causes many problems with the equipments that required steady state voltage especially modern load so it causes malfunction, miss operation and in some times full operation stoppage.It may also cause tripping of contactors and electromagnetic relays and disconnection and less efficiency in rotating machines. Active power filters (APFs) are commonly utilized to ensure power quality in the utility. Series APFs are usually utilized to compensate the voltage unbalance and harmonics by injecting negative-sequence and harmonic voltage to the distribution line through coupling transformers. However, for the micro grid situation, it is uneconomic to install extra APFs for each of the DGs. The DGs includes prime movers and conversion interfaces. The output of the prime movers is DC form (such as PVs, fuel cells, batteries, etc) or AC form (such as wind generators, micro-turbine generators) but usually converted to DC form at first. Then the DC-AC VSIs are utilized as the interfaces to connect the prime movers to the local AC bus of the micro grid. The main function of the VSIs is the power transfer and control. Besides, the voltage unbalance and harmonics compensation ability can be achieved by proper control of the VSIs when the output is of voltage-source type. Some work has been done on voltage unbalance compensation through controlling of the VSIs. Negative-sequence current is injected into the micro grid using the surplus capacity of the inverters to balance the voltage of the micro grid in, in which only unbalanced voltage is solved and the injecting current might be too large under severe conditions. Extra series inverter is used for power quality compensator in, which is uneconomic for the micro grid situation.

1.4 Objective

The main objective is to design load despatch controller in islanded mode of operation of decentralized micro grids because of mismatch between load power and generated power and this causes greater deviation of voltage and frequency from its nominal value .So as a last resort to contain the voltage deviations we need to shed the load at the buses. Existing methods to accomplish this tasks use look up table approach to curtail load which may be based on voltage and frequency deviation but this has a serious loophole of shedding more amount of load then which is required ,hence it may not be optimized . So the LDC designed tries to accomplish the following

1. Design a Load Dispatch Controller in Islanded Micro-grids which would be able to operate based on local voltage measurements and is adaptive in nature.
2. Perform Under-voltage load Shedding to maintain the integrity of grid in cases of voltage collapse and delayed voltage recovery

1.5 Scope of work

The proposed scheme is meant to operate in a fully distributed way, each controller using local information and taking local actions, as under-frequency load shedding controllers do . The objective of this paper is to demonstrate that such a decentralized under-voltage relay could operate reliably. An adaptive feature of the relay lets you optimize the amount of load shed to an extent .By considering two scenarios the relay designed is made more robust to various under-voltage distortions. We can also think of implementing this scheme in a centralized way, by collecting all voltage measurements at a central point, running the computations involved in a single processor, and sending back load shedding orders (with some communication delays to be taken into account).

In this case, additional information exchanges and interactions between controllers may be envisaged without further penalizing the scheme.

1.6 Structure of Thesis

Chapter 1 contains a general introduction to micro grid ,islanded mode of operation and scenario of under voltage in islanded micro grids. This chapter tries to introduce the above said topic in a very general sense so as to articulate the significance and premise of my thesis. This chapter also contains objective of my work so as to clearly elucidate the goals which I tried to accomplish during the courses of my work

Chapter 2 contains excerpts from literature survey done to sort out the relevant literature .The chapter is organized in the way I chronologically narrowed down to the specific literature which I chose to accomplish my objective or which acted as my base paper. Each paper had a a thing to contribute to my understanding of the problem posed to me .

Chapter 3 contains the methodology adopted to formulate problem .It contains all the necessary conditions that needs to be taken care before design of relay which has a huge bearing on relay design .It also elucidates the assumption taken into consideration before designing the relay.

Chapter 4 contains the working principle of the relay designed .The math associated with the design and the way to make the relay adaptive .

Chapter 5 contains the description of the system used and the scenarios of under-voltage without the use of relay.

Chapter 6 contains the improvements in the voltage when the relay comes into picture and also discussion on features of the relay .

Chapter 7 deals with conclusion.

CHAPTER 2

LITERATURE REVIEW OF ISLANDED MICROGRIDS

So as to accomplish my objective survey of literature available in the field was done exhaustively .The literature survey was done in the following broad areas so as to devise final methodology for executing the main process:

1. Islanding mode of operation of micro grids.
2. Load shedding based on grid frequency.
3. Load shedding based on grid voltage.
4. Main reference papers.

2.1 Islanding mode of operation of micro grids

[1] Katiraei *et al.* (2005) investigates (i) pre-planned switching events and (ii) fault events that lead to islanding of a distribution subsystem and formation of a micro-grid.The interface converter of the a generator unit is equipped with independent real and reactive power control to minimize islanding transients and maintain both angle stability and voltage quality within the micro-grid.The studies show that an appropriate control strategy for the power electronically interfaced DG unit can ensure stability of the micro-grid and maintain voltage quality at designated buses, even during islanding transients. This paper concludes that presence of an electronically-interfaced DG unit makes the concept of micro-grid a technically viable option for further investigations. : Paper gives an idea about the modelling of inverter based source and the design of control strategy to employed to get a stable voltage for inverter interfaced source.[2] Katiraei and Iravani (2006) addresses real and reactive power management strategies of

electronically interfaced distributed generation (DG) units in the context of a multiple-DG micro grid system. The emphasis is primarily on electronically interfaced (EI-DG) units. DG controls and power management strategies are based on locally measured signals without communications. Based on the reactive power controls adopted, three power management strategies are identified and investigated. These strategies are based on 1) voltage-droop characteristic, 2) voltage regulation, and 3) load reactive power compensation. The micro grid Eigen structure, based on the developed model, is used to 1) investigate the micro grid dynamic behaviour, 2) select control parameters of DG units, and 3) incorporate power management strategies in the DG controllers. The model is also used to investigate sensitivity of the design to changes of parameters and operating point and to optimize performance of the micro grid system. The results are used to discuss applications of the proposed power management strategies under various micro grid operating conditions. This paper gives detailed explanation of the control strategy employed to stabilise the voltage and power management strategies .It also illustrates the design of various controllers used.In[3] Yu *et al.* (2016) Droop control strategy enables the micro grid switch between grid-connected and islanded mode flexibly, and easily realizes the plug and play function of distributed generation and loads, which has recently aroused great concerns. However, small disturbances may occur during the changing process and eventually yield transient oscillation, thus the focus of microgrid control is how to switch smoothly within different operation modes. In order to improve the dynamic characteristics of an inverter-based microgrid, this paper derived a precise small signal state-space model of the whole microgrid including droop controller, network, and loads. The key control parameters of the inverter and their optimum ranges, which greatly influence the damping frequency of oscillatory components in the transient response, can be obtained through Eigenvalue analysis. In addition, genetic algorithm is introduced to search for optimal settings of the key parameters. [4] Lei *et al.* (2009) discusses islanding control of power electronics interfaced distributed generation (DG) systems in micro grids. Particularly, the following topics will be addressed: micro grid system configurations and features, grid-connected system control mode, transient analysis during power outage, islanding detection and load shedding, standalone system control mode, synchronization in reconnection. This paper gives detailed explanation of the control strategy employed to stabilise the voltage and power management strategies .It also illustrates the design of various controllers used to control the distributed generators. [5] Balaguer *et al.* (2011)discussins islanded mode of operation, it is important for the micro grid to continue to provide adequate power to the load. Under normal operation, each DG inverter system in the micro grid usually works in constant current control mode in order to provide a preset power to the main grid. When the micro grid is cut off from the main grid, each DG inverter system must detect this islanding situation and must switch to a voltage control mode. In this mode, the micro grid will provide a constant voltage to the local load. This paper describes a control strategy that is used to implement grid-connected and intentional-islanding operations of distributed power generation. This paper proposes an intelligent load-shedding algorithm for intentional islanding and an algorithm of synchronization for grid reconnection.

After gaining enough knowledge on method of stabilization of source after intentional islanding and getting required information on design of controllers which is to be employed to get stable voltage and the some insight on how load shedding in carried in practical sense

2.2 Load shedding based on grid frequency

[6] Zhang *et al.* (2014) presents frequency stability is one of the key targets needed when an islanding operation occurring in a distribution system or a micro grid. To balance the generation and demand all the time, load shedding may need to apply to a distribution system or a micro grid which disconnected from the main grid. However, it is difficult to determine the accurate amount of load to be reduced in a real system, as the frequency is changing all the time. In addition to this, economic factors including reliability index and consumersâĂŹ willingness need to be taken into accounted when making the decision except ensuring system stability. This paper proposes a novel load shedding strategy by considering power stability with economy in load shedding for a distribution system with distributed generations such as CHP, small wind and solar panels. The proposed strategy by classifying load into heavy and light groups is adopted, ranking is based on willingness to pay, frequency threshold and rate

of change of frequency (RoCoF). [7] Ceja-Gomez *et al.* (2012) proposes and test a new systematic approach to set load shedding under-frequency relays that replaces much of the conventional simulation-based trial-and-error heuristics by a mixed-integer linear program that can then be solved by commercially available highly efficient solvers such as CPLEX. The new formulation can account for an arbitrary number of random generator outages and for the particularities of the power system such as inertia, damping and regulation parameters, and under-frequency/time limitations. The under-frequency relays are characterized by a sequence of frequency set points and allowed time spans below such levels together with the amount of load shedding needed to meet all specified time and frequency criteria. The objective function is to minimize the average amount of load shed over a set of random generator outages. [8] Malekpour *et al.* (2008) discusses a genetic algorithm (GA) based optimal load shedding that can apply for electrical distribution networks with and without dispersed generators (DG). Also, the proposed method has the ability for considering constant and variable capacity deficiency caused by unscheduled outages in the bulked generation and transmission system of bulked power supply. The genetic algorithm (GA) is employed to search for the optimal load shedding strategy in distribution networks considering DGs in two cases of constant and variable modelling of bulked power supply of distribution networks. Electrical power distribution systems have a radial network and unidirectional power flows. With the advent of dispersed generations, the electrical distribution system has a locally looped network and bidirectional power flows. Therefore, installed DG in the electrical distribution systems can cause operational problems and impact on existing operational schemes. Introduction of DGs in electrical distribution systems has introduced many new issues in operational and planning level. Load shedding as one of operational issue has no exempt. The objective is to minimize the sum of curtailed load and also system losses within the frame-work of system operational and security constraints.[9] Hajimohamadi and Bevrani (2013) discusses the need of , having acceptable voltage and frequency is necessary in a microgrid (MG). This issue is realized by grid in grid-connected mode. But in islanded mode, it depends on proper controllers in primary, secondary and emergency levels. Security in MG following a severe disturbance can be established through emergency control like shutdown of a unit, demand side management, islanding and load shedding. In this paper, a controller is designed to stabilize

MG performance during islanding. Also, a load shedding plan as one of the last actions to prevent blackout of isolated system is presented.

All these approaches could not be utilized as according to the scenario presented to me the sources were inverter interfaced with grid so frequency could not be used effectively as a criterion for load shedding and also the methods presented were dependent on communication infrastructure which is out of the scope of my project

2.3 Load shedding based on grid voltage

[10] Vandoorn *et al.* (2011)In the islanded operating condition, the micro grid has to maintain the power balance independently of a main grid. Because of the specific characteristics of the micro grid, such as the resistive lines and the high degree of power-electronically interfaced generators, new power control methods for the generators have been introduced. For the active power control in this paper, a variant of the conventional P/f droop control strategy is used, namely the voltage-droop controller. However, because of the small size of the micro grid and the high share of renewable with an intermittent character, new means of flexibility in power balancing are required to ensure stable operation. Therefore, a novel active load control strategy is presented in this paper. The aim is to render a proof of concept for this control strategy in an islanded micro grid. The active load control is triggered by the microgrid voltage level. The latter is enabled by using the voltage-droop control strategy and its specific properties. It is concluded that the combination of the voltage-droop control strategy with the presented demand dispatch allows reliable power supply without inter-unit communication for the primary control, leads to a more efficient usage of the renewable energy and can even lead to an increased share of renewable in the islanded micro grid. This paper gives a direct relationship between power and voltage in a low voltage micro grids which has been exploited in my work .So voltage can be used directly as a criterion for load shedding but it has to be enabled by combining the voltage droop and P/V droop controllers as they influence micro grid voltage .this paper implements load shedding without any aid of communication infrastructure .In totality this paper gave me a very useful insight into the way I have to approach the problem [11] Vandoorn *et al.* (2010*a*)

discusses about, new control methods for these inverters have to be developed. In this paper, a control strategy based on the specific characteristics of the distribution grid is proposed. The micro grid power is balanced by modifying the set-value of the grid voltage amplitude at the inverter ac-side according to changes of the dc-bus voltage of the DGs. In this way, straight-forward power balancing and voltage control are achieved and frequent changes of the generated power are avoided. [10] Vandoorn *et al.* (2011) uses three types of controllers to accomplish under voltage load shedding viz $\frac{V_g}{V_{dc}}$droop controller ,$\frac{P_{dc}}{V_g}$ droop controller and Q/fdroop controller so as to accomplish under voltage load shedding .This paper details about ,$\frac{P_{dc}}{V_g}$ controller .This controller stabilises the power delivered by the inverter interfaced source using feedback.[12] Vandoorn *et al.* (2010*b*) discusses about coordinated integration of the increasing amount of distributed generators in the distribution network, the micro grid has been presented. For the islanded operating condition of the micro grid, the conventional approaches for grid control are no longer applicable as the micro grid characteristics differ significantly from those of conventional power systems. Therefore, in this paper, the reactive power control by means of a reactive power/frequency droop control strategy is studied in an islanded micro grid. The active power on the other hand, is controlled by using a droop control strategy of the dc-bus voltage to the grid voltage amplitude. It is shown that the combination of the aforementioned control methods gives good results concerning reactive power sharing and avoidance of circulating currents. Also, a reactive power limiting procedure is incorporated in the droop controller. This paper details Q/f droop controller used in [10] Vandoorn *et al.* (2010*a*),[11] Vandoorn *et al.* (2011)and [12] Vandoorn *et al.* (2010*b*) testify the fact that in islanded micro grids with power electronic interfaced sources and with resistive line characteristics Q is related to f and P is related to V .This information is an important premise on which further work of my project is based.[13] Balanathan *et al.* (1998) presents a technique for under voltage load shedding (UVLS) in power systems. The under voltage load shedding criterion has been developed using a dynamic load model. The parameters of the dynamic load model are estimated online using a nonlinear least squares technique, namely the Gauss-Newton method. The amount of load to be shed is calculated using the parameters of the dynamic load model. In the event of a voltage unstable situation, the proposed under voltage load shedding criterion can be used to calculate the minimum amount of load to be shed at any point in time to avoid a voltage collapse. The criterion is general and can be applied to any power system. From this paper the idea of dynamic load is taken which helps in calculation of amount of load to be shed and the time at which it must be shed so that amount of load to be shed is minimized .This paper gives a deep insight of dynamic load which plays a very crucial role in defining a load when its type and parameters are not specified . [14] Laaksonen *et al.* (2005) presents voltage and frequency control of islanded micro grid after intentional and unintentional switching events are investigated. The weak low voltage (LV) network based micro grid consists of two inverter based distributed generation (DG) units. One unit is a storage (battery) unit and the other is a photovoltaic (PV) cell. In this case the battery inverter with rapid response is considered to act as a master and it has the main responsibility to control the voltage and frequency in micro grid when islanded from the main distribution network. The studies are performed on a PSCAD simulation software package. Simulation studies show the voltage - active power and frequency - reactive power dependency in weak LV network. The studies also show that in order to maintain frequency balance in islanded micro grid, there is need for a reference sine wave generator inside master unit which imitates the main network phase voltages and gives the input for master units' (battery storage) PLL (Phase Locked Loop) during islanding. This paper gives explicit relation between P/V and Q/f for a simple system which gives a mathematical expression for this relation for a simple system and this relation can be extrapolated to multi generation and load system and hence relation between P/V is firmly established .[15] Lopes *et al.* (2006) describes and evaluates the feasibility of control strategies to be adopted for the operation of a microgrid when it becomes isolated. Normally, the microgrid operates in interconnected mode with the medium voltage network; however, scheduled or forced isolation can take place. In such conditions, the microgrid must have the ability to operate stably and autonomously. An evaluation of the need of storage devices and load shedding strategies is included in this paper. : Load shedding strategyfollowed in [10] Vandoorn *et al.* (2010*a*) is the same elucidated in this paper but this paper uses P/f relation to accomplish the load shedding but in micro grids and because of its essential characteristics P/V relation is used to shed the load.

2.4 Main Papers of Reference

The following papers are the main reference papers which form the base of my work . In [16] Otomega and Cutsem (2007) A new load shedding scheme against long-term voltage instability is proposed. It uses a set of distributed controllers, each monitoring transmission voltages in a zone and controlling a group of related loads. Each controller acts in closed-loop, shedding amounts that vary in magnitude and time according to the evolution of its monitored voltage. The whole system can operate without information exchange between controllers, the latter being implicitly coordinated through network voltages.This is the base paper for my work .The strategy for under voltage load shedding is taken which takes only local measurements but this paper uses a lot of empirically determined parameters as an improvement uses only one empirically determined constant and all other parameters are determined deterministically and adaptively . [17] Kolluri *et al.* (2015) presents fault-induced delayed voltage recovery (FIDVR) as a major concern in bulk electric systems, especially in high load growth areas of the system which may be limited in generation and transmission. As part of an overall emergency plan to manage exposure to low voltage conditions and resulting voltage instability under summer peak load conditions, a fast-acting, localized, relay-based under-voltage load shedding (UVLS) scheme has been implemented for EntergyâĂŹs Western Region. This paper describes the planning considerations and design criteria, followed by implementation details of the relay operation logic programmed using a standard microprocessor based multi-functional relay. This paper deals with a unique case of under voltage where the recovery of voltage is very slow .This case has also been considered as it is a special case encountered in case of small ac motor loads.[18] Ye *et al.* (2015) proposes a new adaptive load shedding method based on the under frequency and under voltage combined relay. With considerations on influences of frequency and voltage dynamics on the load active power, this method uses real-time measured local responses to calculate the amounts of under frequency load curtailments and under voltage load curtailments, respectively, and adopts the larger one as the practical amount of load curtailments. Furthermore, this method transmits the practical amount of load curtailments to the under frequency and under voltage combined relay, thus triggering local successive load shedding This paper is of seminal importance as far as calculation of optimum amount of load to be shed is concerned .

CHAPTER 3

FORMULATION OF LOAD SHEDDING

3.1 Introduction

The problem posed before me was to design a relay which would shed the load based on voltage. In conventional power relation between the expressions for **Real Power (P)** and **Reactive Power (Q)**

$$P = \frac{\partial P}{\partial V}\Delta V + \frac{\partial P}{\partial f}\Delta f \tag{3.1}$$

P and **f** are tightly coupled so frequency has more impact on average and real power. Similarly **Q** and **V** are tightly coupled so voltage has more impact on reactive power.

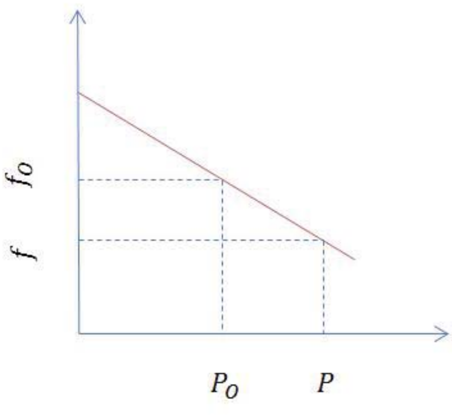

Figure 3.1: power vs frequency

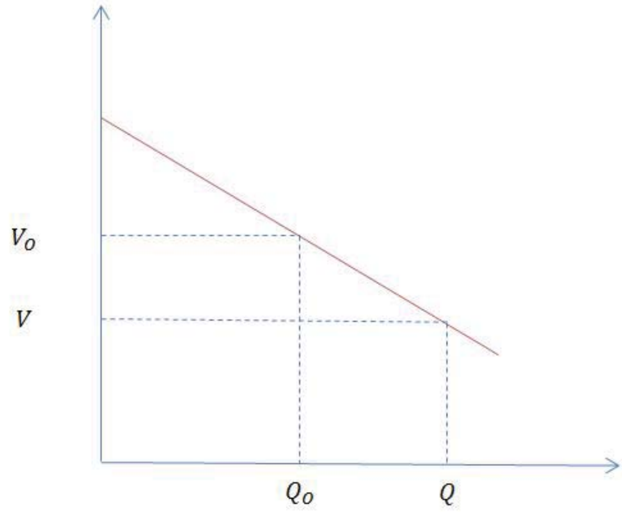

Figure 3.2: reactive power vs voltage

but the islanded micro grid considered has inverter interfaced sources which maintain grid frequency and also the line characteristics are largely resistive so as far as **Real Power (P)** is concerned it is tightly coupled with *voltage* and similarly **Reactive Power (Q)** is tightly coupled to *frequency*

3.1.1 Mathematical Relations

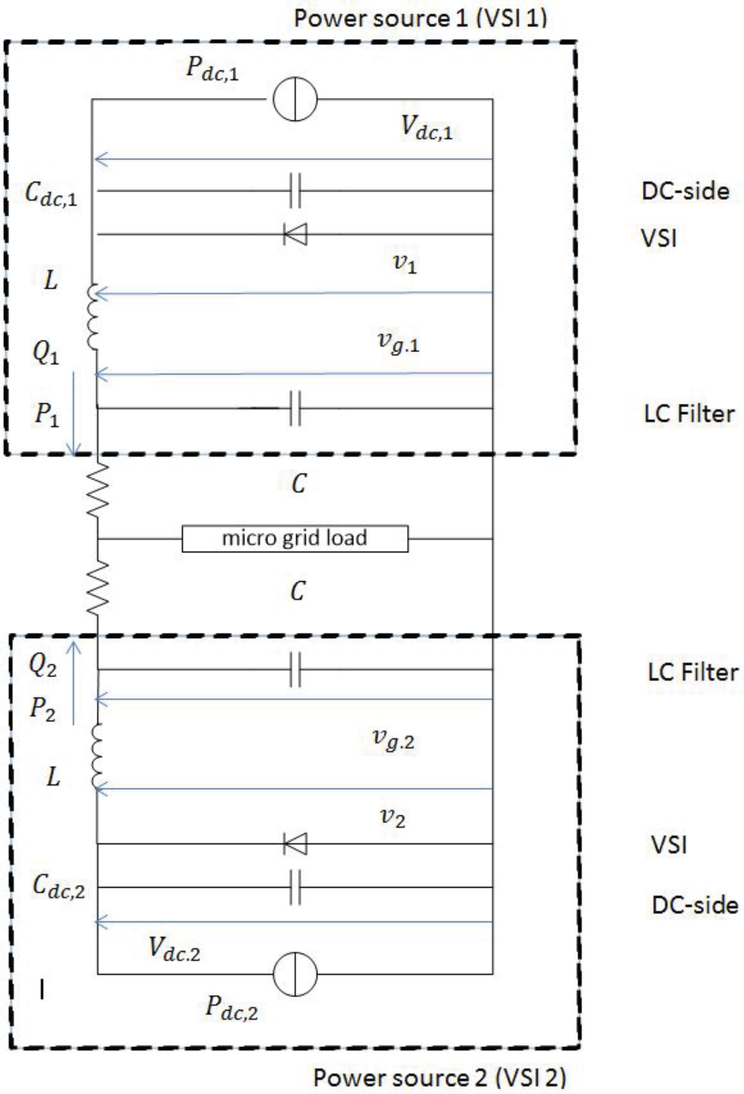

Figure 3.3: Microgrid configuration for the case of two inverter-interfaced primary energy sources

The reactive power Q injected into the grid by a power source is calculated by using:

$$Q = Im(v_g, i_g^*) \tag{3.2}$$

with$v_g$the voltage of the power source: $v_g = V_g e^{j\delta_1}$in the complex notation, $i_g$the line current and $i_g^*$the complex conjugate ofi_g. As microgrids are low-voltage networks, their lines are mainly resistive and therefore, according to fig 3.3 , the load current is i_g

determined by:

$$i_g = \frac{v_g - v_1}{R_1} \tag{3.3}$$

with$v_1$the load voltage $v_1 = V_1 e^{j\delta_2}$.The load phase angle $\delta_2$can be chosen as zero as voltage angles are only determined as relative quantities therefore $v_1 = V_1$.The reactive power (3.2) can be rewritten as

$$Q = Im[V_g(cos\ \delta_1 + jsin\ \delta_1)\frac{V_g(cos\delta_1 - jsin\ \delta_1) - V_1}{R_1} \tag{3.4}$$

or equivalently $Q = -\frac{V_g V_1}{R_1}\ sin\ \delta_1$ asδ_1 is approximately equal to δ_2, $sin\ \delta_1$is approximately equal to δ_1 and $cos\ \delta_1$ is approximately equal to 1.By using these approximations Q can be expressed as

$$Q = -\frac{V_g V_1}{R_1}\delta_1 \tag{3.5}$$

From (3.5), an increase of Q leads to a decreased phase angle$\delta_1$of the voltage of the power source. Note that in the mainly resistive micro grid, this statement is valid from a generators point of view for the current reference, with a positive current flowing from generator to load. In this case, with RL-loads, the phase angle$\delta_1$is negative, thus, an increase of Q leads to an increased absolute value of the phase angleδ_1 .The active power P can be expressed

$$P = \frac{V_g}{R_1}(V_g - V_1\ cos\ \delta_1) \approx \frac{V_g}{R_1}(V_g - V_1) \tag{3.6}$$

From (3.5) and (3.6) it is concluded that a decoupling of P/Q and the voltage amplitude/frequency is achieved in micro grids with resistive characteristics.Q is predominantly dependent on the frequency, or equivalently phase difference over the line, while P is determined mainly by the voltage difference over the line. This dependency is the opposite of the one in inductive systems with mainly a P/f and Q/V linkage

3.2 Design Of Controllers

The following section briefly talks about working of controllers which tries to regulate the voltage and frequency of sources as their proper functioning is essential for reliable functioning of micro grid and the need for load shedding arises only after full potential of controllers has been exhausted .We will briefly discuss the three controllers which are used to accomplish the stabilization of voltage and frequency of sources

The active power controller of the generators is based on two control strategies, with their operation dependent on the RMS microgrid voltage. In a voltage band around the nominal micro grid voltage, only $V_g/V_{dc}$the droop control strategy of is applied, keeping the generated power constant and where,$V_g$the RMS micro grid voltage, is drooped with,$V_{dc}$the dc-link voltage of the power source. If the microgrid voltage exceeds this band, also aP_{dc}/V_g droop controller is turned on, which changes the generated power $P_{dc}$and avoids violation of the voltage limits. The control algorithm deals with the specific properties of the micro grid, such as the lack of inertia and the resistive line characteristics and it is fully distributed as well. As most DG units are power-electronically interfaced to the electrical system, they lack significant inertia, upon which the conventional P/fdroop control is based. The applied droop controllers use the voltageV_{dc} as communication for active power which thus not depends on inertia. Also, $V_{dc}$is a local parameter, while the grid frequency is equal for all generators in the conventional power system. The resistive line characteristics cause P/Vlinkage, which is the basic principle of these controllers. The control is performed without communication and avoids single-points of failure such as masters or central controllers. Also, as many DG units are interfaced to the micro grid via VSIs, the power storage capacity of the dc-link capacitors is actively addressed for the control.

3.2.1 V_g/V_{dc} Droop Control Strategy

The V_g/V_{dc}droop control strategy is based on the (transient) storage capabilities of the dc-link capacitors. An increase of dc-link voltage indicates an excess of dc-power P_{dc}compared with the power absorbed by the electrical network. This voltage V_{dc}will increase, for example, when the microgrid load decreases or when the generated power increases. A decreasingV_{dc} on the other hand indicates that the VSI injects more power in to the electrical network than the power source generates. Therefore, changes ofV_{dc} indicate changes of the state of the micro grid power. Hence, theV_g/V_{dc} droop controller

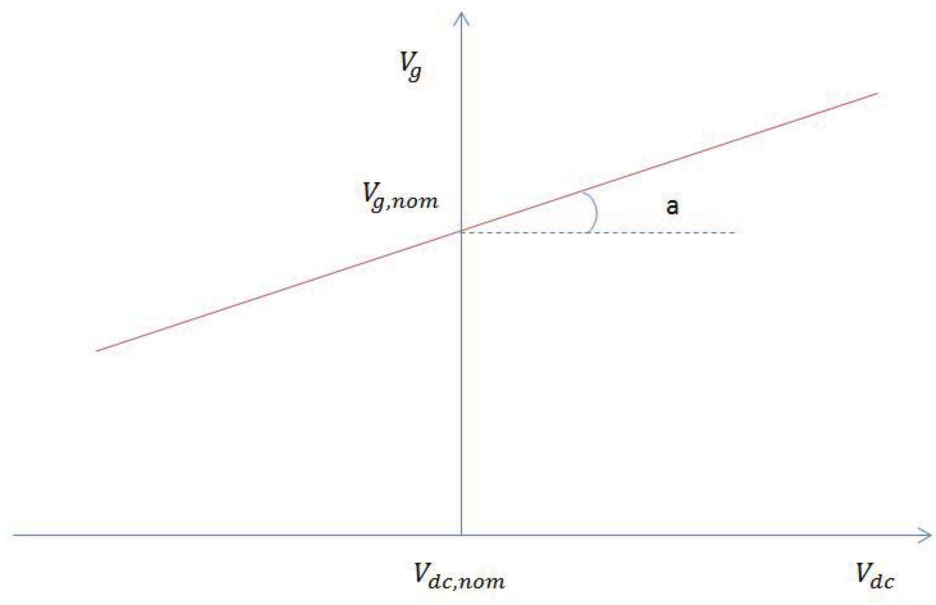

Figure 3.4: Droop controller with V_g as a function of V_{dc}

changes the reference RMS micro grid voltage,V_g proportionally to $V_{dc} - V_{dc,nom}$, following the droop characteristic of Fig 3.4 and where “nom” denotes nominal values

$$V_g = V_{g,nom} + a\,(V_g/V_{dc}) \tag{3.7}$$

Even a slight change of, $V_g$leads to a change of the power delivered to the electrical network by the inverter. This effect is realized by a natural balancing due to resistive loads and micro- grid lines, and by intelligent lo ads that use voltage as trigger for the active load control

3.2.2 P_{dc}/V_g Droop control strategy

This V_g/V_{dc} droop control strategy delays changing the output power of the generators by slightly varyingV_g . Still, the variations ofV_g need to remain in a tolerated microgrid voltage band (for example, 0.92–1.08 $V_{g,nom}$) . However, not changing the output of all DG units may result in excessive voltage rises. To overcome this problem, it is necessary to control the active power of the DG units. However, to avoid communication and central controllers, aP_{dc}/V_g droop controller with negative slope is used to change P_{dc}according toV_g. This limits the variations ofV_g, because of the P/Vlinkage that exists in micro grids. In the presented work, on the other hand, a fully distributed control of the generators without master inverter is used and theP_{dc}/V_g droop control strategy is combined withV_g/V_{dc} droop control

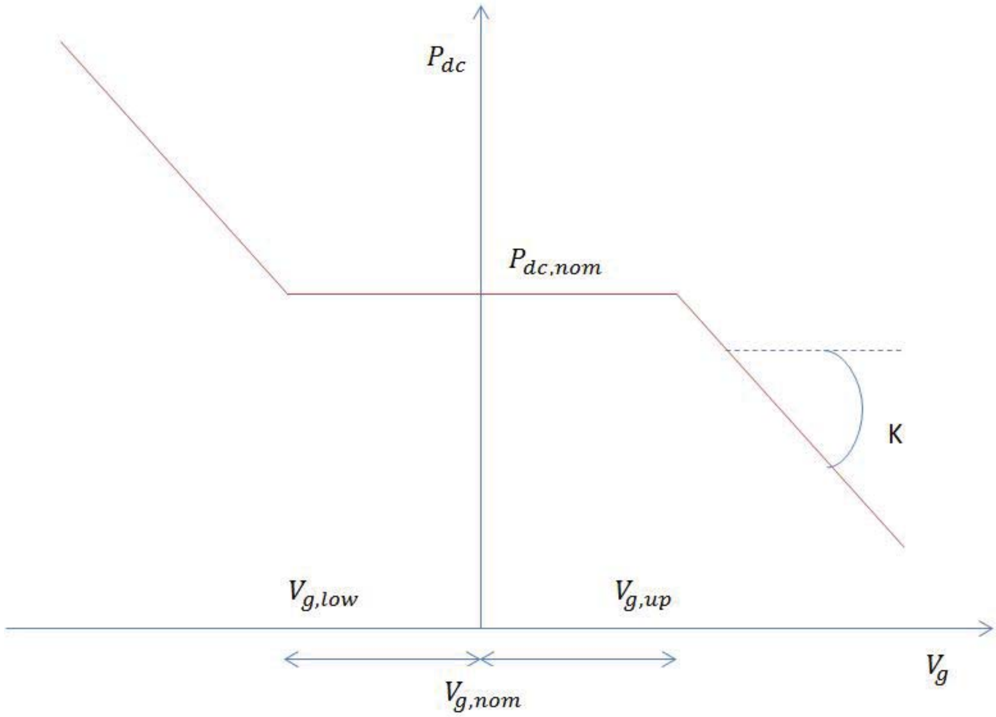

Figure 3.5: P_{dc}/V_g droop controller

As shown in Fig. 3.5, theP_{dc}/V_gdroop controller only operates if a certain micro grid voltage is exceeded. This voltage is determined by the adjustment voltages $V_{g,up}$ and $V_{g,low}$, which identify a voltage band that does not exceed the tolerated micro grid voltage band. In case these adjustment voltages are not exceeded, P_{dc} remains unchanged and only theV_g/V_{dc} droop control strategy is used.

noindent The combined operation of the V_g/V_{dc} and P_{dc}/V_g droops is shown in Fig.**??**.This figure shows that if V_g , calculated according to the V_g/V_{dc}droop control, exceeds the upper adjustment voltage$V_{g,nom}+V_{g,up}$,theP_{dc}/V_g droop controller decreasesP_{dc} , and it increasesP_{dc} if V_g is lower than $V_{g,nom} - V_{g,low}$. In these two conditions, the two droop

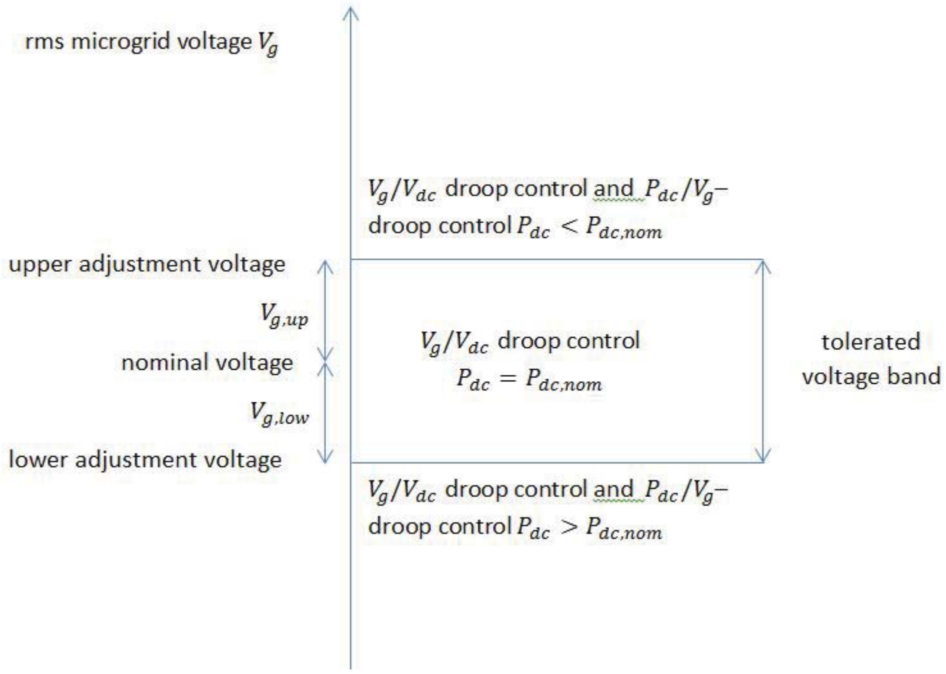

Figure 3.6: P_{dc}control as a function of V_g: adjustment voltages $V_{g,up}$ and $V_{g,low}$

controllers operate together, while otherwise, with only theV_g/V_{dc} droop controller,P_{dc} would remain equal to$P_{dc,nom}$, which is, for example, the nominal power or the maximum available dc power, determined by maximum power point tracking (MPPT). The power$P_{dc,nom}$ is determined by the primary energy source and thus not by the VSI control algorithm. Changing is also dependent on the energy source, e.g., by altering the fuel intake, abandoning a MPPT control algorithm or addressing power storage.

The implementation of the controllers is depicted in Fig. 3.7. Firstly, depending onV_{dc}, $V_g$is calculated with theV_g/V_{dc} droop controller. Secondly, depending onV_g,$P_{dc}$is changed or remains the same by using theP_{dc}/V_g droop control strategy with adjustment voltages$V_{g,up}$ and$V_{g,low}$ .Avoltagecontroller determines the duty ratios of the VSI, with reference RMS micro- grid voltageV_g determined by active power control and reference frequency determined by the reactive power controller

3.2.3 Adjustment Voltage

The adjustment voltages $V_{g,up}$ and $V_{g,low}$and depend on the power source. For example, a distinction can be made between variable and non-variable power sources. For variable, controlled (often non-renewable) power sources, a narrow constant-power band, with low $V_{g,up}$ and high $V_{g,low}$ can be handled. Therefore, smaller variations of V_g from $V_{g,nom}$ address the P_{dc}/V_g droop controller to change P_{dc} . This enables to fully exploit the power control characteristics of the power source. In this way, less voltage variation in the microgrid is obtained as the power source acts dynamically to limit the voltage changes by changing its output power. For non-variable or slightly variable (often renewable) power sources, is determined externally and therefore, a wide constant-power band, with high $V_{g,up}$and $V_{g,low}$, can be applied. In this way, changing the output power of this power source is delayed and is only addressed to limit too large voltage variations in the microgrid. This is also interesting for CHP units where the heat is the primary driver. By also including P_{dc}/V_g the droop control strategy in these less-controllable power sources, in case of high microgrid voltage, they can still generate some power by lowering their output power whereas they would normally shut down because of overvoltage tripping if P_{dc} would remain constant. Because of the increasing share of renewable energy sources, active dispatching of these units in the small scale microgrids will be required. This control strategy makes this possible, while still delaying the power changes of the renewable and first, which depends on the microgrid voltage, exploiting the controllable units. In this way, a better usage of the renewable energy can be achieved.

3.2.4 Reactive Power Control

The conventional power system control is largely based on a decoupling of the active power P and the reactive powerQ ; and on the linkage between Q and V . Therefore, Q/V droops are used.However, in themicrogrid, this linkage is not valid, because the lines are mainly resistive as microgrids are generally weak low-voltage distribution networks, opposed to the mainly inductive transmission system. From references it follows that a linkage between the reactive power Q and the phase differenceδ is valid, in case the inductance may be neglected and with the assumption that is small. Also, the frequency dynamically determines the phase angle . Therefore, in this work, a Q/f droop controller is applied, which is analogous to the conventional Q/V droop control strategy. Fig. 3.8shows the Q/f droop control principle which measures the reactive power flow and droops it to provide the frequency.

By using the aforementioned Q/f droop control strategy, a stable operation of multiple generators is insured without the need for a communication infrastructure. The reactive power sharing between the different generators can be controlled by adjusting the droops

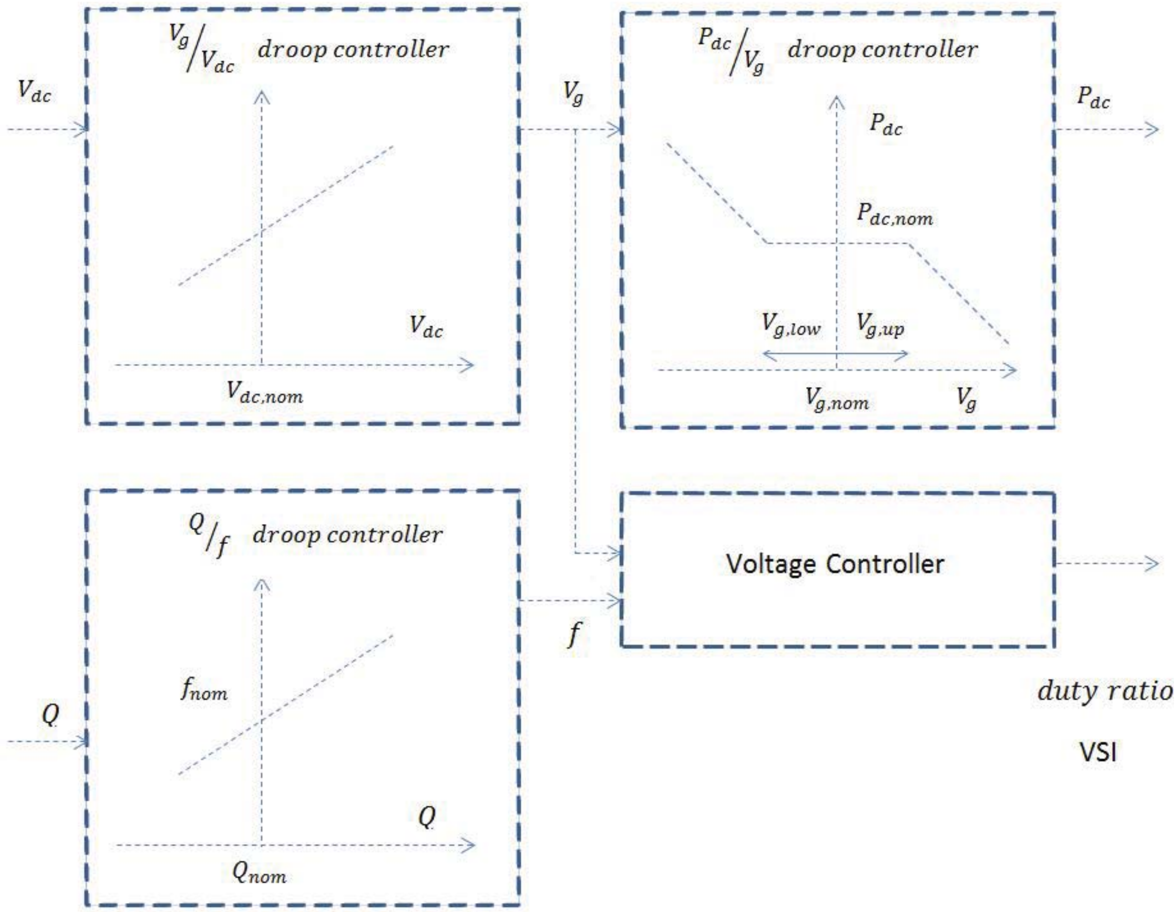

Figure 3.7: Implementation of the Droop Controllers

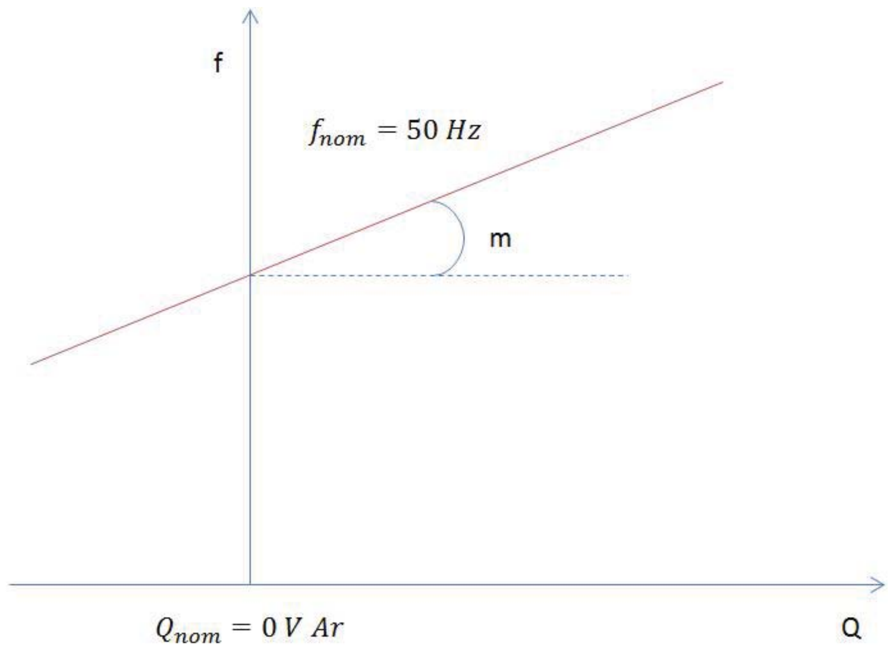

Figure 3.8: Reactive power/frequency droop control

3.2.5 Conclusion

It is concluded that with a proper combined usage ofV_g/V_{dc} and P_{dc}/V_gdroop controllers, a higher degree of renewable and a more efficient usage of the renewable energy can be expected. Still, the renewable can operate in an optimal condition as long as possible. The reason is the usage of different adjustment voltages according to the characteristics of the DG units. Therefore, the changes ofP_{dc} in the slightly controllable units are delayed compared to that of the more dynamical DG units. The tolerance band of the microgrid voltage compared to its nominal value is effectively used, while still, violation of the voltage limits is avoided. Furthermore, theV_g/V_{dc} droop and P_{dc}/V_gdroop control strategies deal with the specific properties of the microgrid and are fully distributed. Also, this active power controller of the generators allows to use the microgrid voltage as a trigger for possible active load control.

3.3 Philosophy of Load Shedding Strategy Adopted

By using the aforementioned active and reactive power control methods for the generators, the possibility of the microgrid voltage to vary between certain limits is effectively used. Therefore, the microgrid voltage can be applied to communicate an excess or deficit of power in the islanded microgrid, which is mainly due to the renewable power in case of proper application of the adjustment voltage.

In the practical system, the kind of load shedding belongs to the family of system protection schemes (also referred to as special protections scheme) (SPS) against long - term voltage instability. An SPS is a protection designed to detect abnormal system conditions and take predetermined corrective actions (other than the isolation of the faulted elements) to preserve as far as possible system integrity and regain acceptable performances

The following SPS design has been chosen

1. **Response based** : Load shedding will rely on voltage measurements that reflect the initiating disturbance (without identifying it) and the actions taken so far by the SPS and by other controllers. On the contrary, an event - based SPS would react to the occurrence of specific events

2. **Rule based** : Load shedding will rely on a combination of rules of the type
   If V $< V_{threshold}$ during t seconds, shed ΔP MW

3. **Closed - loop operation** : An essential feature of the scheme considered here is the ability to activate the rule equation V$<V_{threshold}$ several times, based on the measured result of the previous activations. This closed - loop feature allows the load shedding controllers to adapt their actions to the severity of the disturbance. Furthermore, it increases the robustness with respect to operation failures as well as system behaviour uncertainties. This is particularly important in voltage instability, where load plays a central role but its composition varies with time and its behaviour under large voltage drops may not be known accurately.

4. A **distributed** scheme is proposed for its ability to adjust to the disturbance location.
   It is well known that time, location, and amount are three important and closely related aspects of load shedding against voltage instability. The time available for shedding is limited by the necessity to avoid :
   - Reaching the collapse point corresponding to generator loss of synchronism or motor stalling
   - Further system degradation due to under voltage tripping of field current - limited generators, or line tripping by protections

- The nuisance for customers of sustained low voltages. This requires fast, action even in the case of long - term voltage instability, if the disturbance has a strong initial impact .

As far as long - term voltage instability is concerned, if none of the above factors is limiting, one can show that there is a maximum delay beyond which shedding later requires shedding more . On the other hand, it may be appropriate to activate other emergency controls first so that the amount of load shedding is reduced . The shedding location matters a lot when dealing with voltage instability: Shedding at a less appropriate place requires shedding more. In practice, the region prone to voltage instability is well known beforehand. However, within this region, the best location for load shedding may vary significantly with the disturbance and system topology.

3.3.1 Under voltage Load Shedding using Distributed Controllers

This under voltage load shedding scheme relies on a set of controllers distributed over the region prone to voltage instability . Each controller monitors the voltage V at a transmission bus and acts on a set of loads located at distribution level and having influence on V . Each controller operates as follows:

1. It acts when its monitored voltage V falls below some threshold V threshold .
2. It can act repeatedly, until V recovers above V threshold . This yields the already mentioned closed - loop behavior
3. It waits in between two shedding, in order to assess the effect of the actions taken both by itself and by the other controllers.
4. The delay between successive shedding varies with the severity of the situation.
5. The same holds true for the amount shed.

Under voltage Load shedding using distributed controllers when the rate of recovery of voltage is very slow

Fast voltage collapse and delayed voltage recovery problems have become increasingly important over the last several years as systems become more stressed due to load growth and a general declining trend in system infrastructure investments. Numerous cases of heavily loaded systems experiencing fault-induced voltage problems have been reported in the literature and extensively studied. These studies have shown a clear link between motor load, especially smaller motors, and the tendency of system voltages to experience a fast collapse or slow recovery following fault clearing.

A simple but effective solution was created using a programmable relay.An algorithm which calculates the slope of the voltage recovery trajectory was created based on successive voltage values. This slope, coupled with the most recent voltage value, can be used to establish a first-order (linear) prediction of the time at which the voltage recovery is expected to reach a certain value. (Higher order trajectory approximations were also considered but not selected so as to avoid unnecessary computational burden on the relay platform.) For the contingency recovery criteria presented previously, voltages at load-serving stations where UVLS relays would be located must recover above 0.8 per-unit in 4 s or less. Any slope-based prediction of a recovery time greater than 4.0 s can therefore be used to initiate UVLS operation. This margin in recovery time directly results in minimizing the expected operation of UVLS and increases the overall security of the scheme. This margin also serves to minimize potential issues (e.g., slope calculation sensitivity) in the calculation and prediction of recovery time.

3.4 Dynamic Load Modelling

In analysing the load dynamics it is important to consider the influence of voltage on real power as well as reactive power. For the load model described in this Section it is assumed that the load real power and reactive power dynamics have similar characteristics, butcould be represented independently of each other. For brevity, in the following Section, only the modelling of real power dynamics is described.The load is approximated to have an exponential recovery when subjected to a step voltage disturbance.A useful model that captures this behaviour is shown in Fig. 3.9

The differential equation governing the dynamics represented by the model can be expressed as

$$T_p \frac{dx_p}{dt} = P_s(V) - P \quad ; \quad P = x_p P_t(V) \tag{3.8}$$

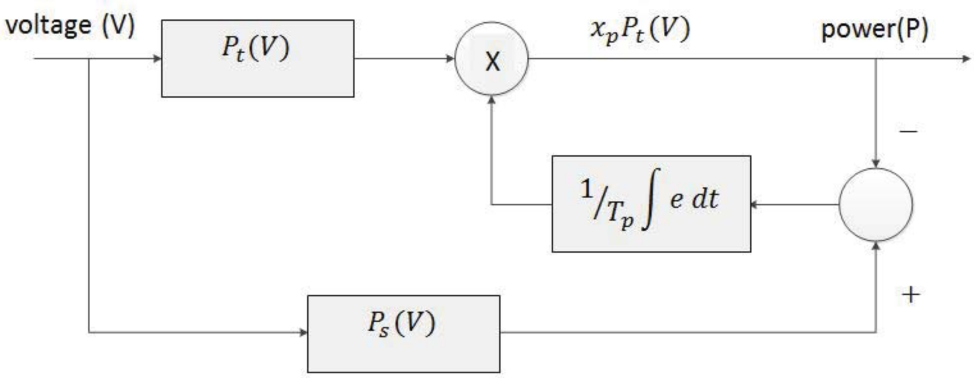

Figure 3.9: General dynamic load model

In the above model, x_p is the state variable, $P_t(V)$ and $P_s(V)$ are the transient and steady state load characteristics, respectively, and T_p is the time constant of the load . In this study, the following polynomial expressions will be used to approximate the transient and steady state load characteristics

$$P_t(V) = c_2V^2 + c_1V + c_0 \tag{3.9}$$

$$P_t(V) = P_0(d_2V^2 + d_1V + d_0) \tag{3.10}$$

where$c_2, c_1, c_0, P_0, d_2, d_1, d_0$ are independent of V When the system is in steady state, the state variable x_p is constant. When the power system is perturbed, the state variable x_p cannot change instantaneously. Hence, the instantaneous load power during the transient period is given by P = $x_pP_t\,(V)$. The mismatch between the steady-state load power and the instantaneous load power is the input to the integration block, which gradually changes the state variable x_p until the error signal fed to the integration is zero. At this point P =$P_s\,(V)$

3.4.1 Estimation of Load Parameters

The dynamic load model (3.8) has the form of a nonlinear system:

$$\dot{x} = f(x, u; \theta) \tag{3.11}$$

whereθ denotes the parameters to be estimated, x is the load state variable and u is the input to the model, which in this case is the load voltage. The dynamic load model in (3.8) can be approximated in the discrete time domain by using the backward Euler approximation

$$\frac{x_k - x_{k-1}}{\Delta t} = (\frac{dx}{dt})_k \tag{3.12}$$

where k,k-1...describe the uniform sampling instances. Applying the above approximation, the dynamic load model used for estimating the model parameters can be expressed as:

$$T_p(x_k - x_{k-1}) = (P_s(V_k) - P(V_k))\Delta t \tag{3.13}$$

$$x_k = \frac{P(V_k)}{P_t(V_k)} \tag{3.14}$$

By manipulating the above equations and the polynomial expressions for the transient (3.9) and steady state (3.10) load characteristics, the discrete load model can be expressed as:

$$P(V_k) = \frac{P(V_k)}{P_t(V_{k-1})}[\frac{P_s(V_k)P_t(V_{k-1})V_k + T_pP(V_{k-1})}{T_p + P_t(V_k)\Delta t} \tag{3.15}$$

where

$$P_s(V_k) = P_0(d_2{V_k}^2 + d_1V_k + d_0) \tag{3.16}$$

$$P_t(V_k) = c_2{V_k}^2 + c_1V_k + c_0 \tag{3.17}$$

Δt =sampling time

The discrete load model (eqn. 19) can be further simplified by defining a normalised form of the transient load characteristics, such that$P_t^{'} = P_t(V_k)/T_p$ Consequently the discrete load model can be expressed as:

$$P(V_k) = \frac{P_t^{'}(V_k)}{P_t^{'}(V_{k-1})}[\frac{P_s^{'}(V_k)P_t^{'}(V_{k-1})V_k + P(V_{k-1})}{1 + P_t^{'}(V_k)\Delta t}] \tag{3.18}$$

$$P_s^{'}(V_k) = d_2^{'}{V_k}^2 + d_1^{'}V_k + d_0^{'} \tag{3.19}$$

$$P_t^{'}(V_k) = c_2^{'}{V_k}^2 + c_1^{'}V_k + c_0^{'} \tag{3.20}$$

$$c_2{}' = \frac{c_2}{T_p}, c_1{}' = \frac{c_1}{T_p}, c_0{}' = \frac{c_0}{T_p}, d_2{}' = P_0 d_2, d_1{}' = P_0 d_1, d_0{}' = P_0 d_0 \tag{3.21}$$

The parameters to be estimated in the discrete load model(3.18) are

$$[\theta] = [c_2{}', c_1{}', c_0{}', d_2{}', d_1{}', d_0{}'] \tag{3.22}$$

A nonlinear least squares estimation technique is used for evaluating these parameters. Suppose we have a set of N observations of measured variables such as real power and voltage. The estimation process is to find a set of optimum parameters$[\theta]$so as to minimise the error between the measured output$(P\,(t_j))$) and the predicted output$\left(\overline{P}\,(t_j)\right)$obtained using the estimated parameters. A least squares error function is formed:

$$E_N(\theta) = \sum_{j=1}^{N} [(P(t_j) - \overline{P}(t_j)] \wedge 2 \tag{3.23}$$

The criterion is to minimize the estimate error $E_N(\theta)$ using an optimisation algorithm. The aim is to fit the data (t_j, P_j),j=1....N with a model $\overline{P}(\theta, t)$that is nonlinear in θ.

The estimation error $E_N(\theta)$is minimised using the Gauss-Newton method .Gauss-Newton method is an iterative method to solve the nonlinear parameter estimation. The new estimate is computed as:

$$\theta_{n+1} = \theta_n - (J(\theta)^T J(\theta))^* J(\theta)^T R(\theta) \tag{3.24}$$

where T is the transpose ,*is the pseudo inverse

$$J(\theta)_{lm} = \frac{\partial r_l(\theta)}{\partial \theta_m}, r_j = P_j - \overline{P}(\theta, t_j) and R(\theta) = [r_1, r_2 \ldots\ldots..r_N]^T \tag{3.25}$$

The estimate is iteratively computed until the difference between consecutive iterates is less than a prescribed tolerance.

Therefore, using the above algorithm, the best set of load parameters to represent the measured load response can be found. The estimated parameters will also reflect any small changes in load during the measured load recovery period. The parameters required for the UVLS criterion are$d_2{}', d_1{}', d_0{}'$. However the transient characteristics and the load time constant can also be obtained by using (3.15) in the optimisation algorithm.

3.5 Voltage Characteristics of Load

The active power of load, which is proportional to system frequency and load voltage, can be expressed by the following power function load model :

$$P_L = P_{LO}(\frac{V}{V_{LO}})^{\alpha} \tag{3.26}$$

whereP_L and P_{LO}denote the practical and rated load active power respectively, V and $V_{LO}$are the practical and rated load voltage respectively α is between 0.5∼2.The value of α is to be determined by statistical data ,steady state experiment and the real-time measured information.

When the load voltage drops during disturbances, the load active power decreases, thus accelerating the recovery of the voltage. However, if UVLS is triggered due to severe drop of the voltage, the load active power will increase after load shedding, which weakens the effect of load shedding. Therefore, it is necessary to consider the negative effect of load characters on load shedding control and adjust the amount of load curtailments according to the frequency and voltage dynamics.

CHAPTER 4

METHODOLOGY OF UNDERVOLTAGE LOAD SHEDDING

Here we will be describing the function of the relays designed .The broad principles on which design was already described in Chapter 3 . Here the two scenarios of under voltage are considered .Firstly the scenario when voltage is collapsing is considered i.e.$dV/dt < 0$ is considered and also the case $dV/dt > 0$ i.e. when the voltage is recovering but in a delayed is also considered. The events leading to both the cases are considered in previous chapters .Here we will be also elucidating the methodology employed to shed the load in adaptive matter .

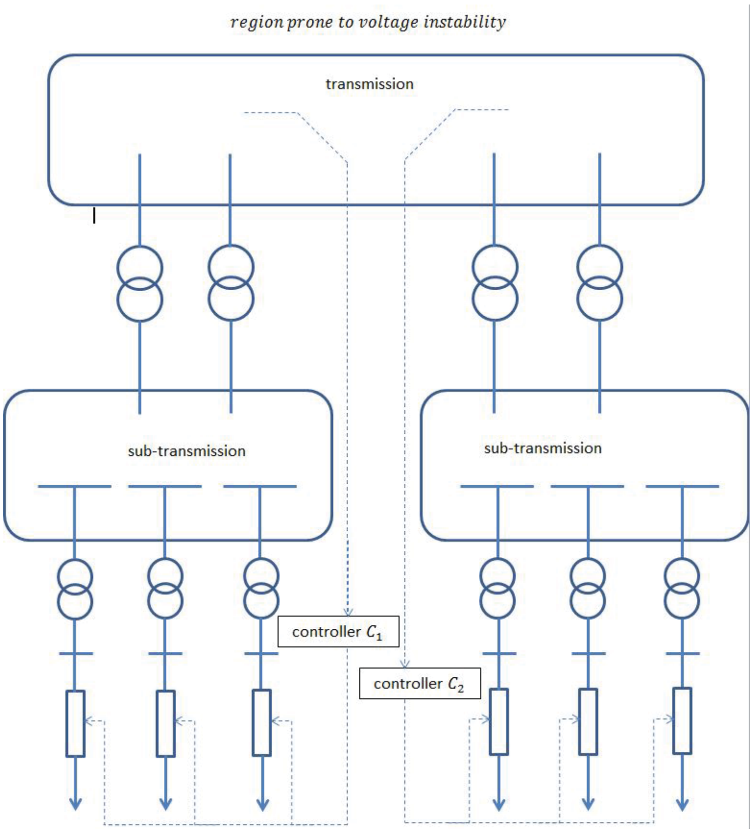

Figure 4.1: Overall structure of the proposed scheme

4.1 Individual Controller Design When Voltage is Collapsing ($dV/dt<0$)

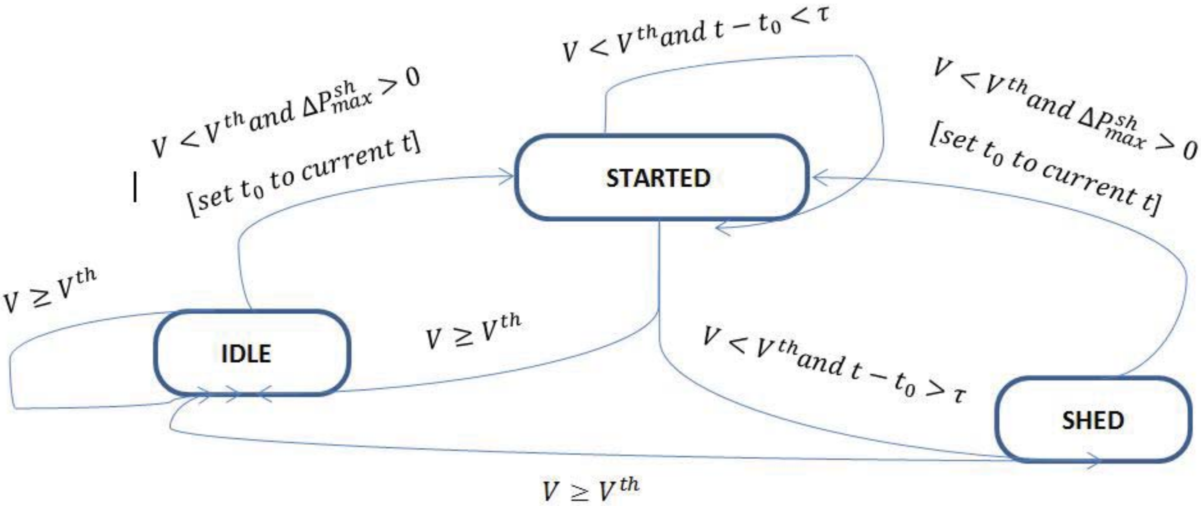

Figure 4.2: Logic of individual load shedding controller (within brackets :action when the transition takes place

The operation of an individual controller is described in 4.2 in the form of an automaton. As long as V remains above the specified threshold, the controller is idle, while it is started as soon as a (severe) disturbance causes V to drop below V^{th} . Let t_0 be the time where this change takes place. The controller remains started until either the voltage recovers, or a time τ is elapsed since t_0 . In the latter case, the controller sheds a power ΔP^{sh} and returns to either idle (if V recovers above V^{th}) or started state (if V remains smaller than V^{th}). In the second case, the current time is taken as the new value of t_0 and the controller is ready to act again (provided of course that there remains load to shed).

The delayτ depends on the time evolution of V as follows. A block of load is shed at a time such that:

$$\int_{t_0}^{t_0+\tau} (V^{th} - V(t))dt = C \tag{4.1}$$

where C is a constant to be adjusted. This control law yields an inverse-time characteristic: the deeper the voltage drops, the less time it takes to reach the value C and, hence, the faster the shedding. The larger C , the more time it takes for the integral to reach this value and hence, the slower the action

Furthermore the delay τ is lower bound :

$$\tau_{min} < \tau \tag{4.2}$$

to prevent the controller from reacting on a nearby fault. Indeed, in normal situations time must be left for the protections to clear the fault and the voltage to recover to normal values.

4.1.1 Calculation on Under Voltage Load Curtailments

As it is known, the transient voltage can drop to a very low value in seconds after the disturbance such as system disconnection. In order to avoid voltage collapses as soon as shed signal is obtained under voltage load curtailments are calculated without time delay.

The amount of under voltage load curtailment is calculated by

$$\Delta P_{LV} = P_L - P_L(\frac{V}{V_{LO}})^{\alpha} \tag{4.3}$$

whereΔP_{LV} is the under voltage load curtailments,P_L is the practical load active power. After load shedding, the load active power P_{LS} should be

$$[P_{LS} = P_L - \Delta P_{LV} = P_L(\frac{V}{V_{LO}})^{\alpha} \tag{4.4}$$

Supposing that the transmission capacity of the power system remains the same after load shedding, which means the amount of active power that the power system can transmit to the load is P_L, the load active power after load sheddingP_{LS} should be equal toP_L after the transient process as shown by Eq.(4.5).

$$P_{LS} = P_L \tag{4.5}$$

The controller acts by opening distribution circuit breakers and may disconnect interruptible loads only. Hence, the minimum load shedding corresponds to the smallest load whose breaker can be opened, while the maximum shedding corresponds to opening all the manoeuvrable breakers. Furthermore, to prevent unacceptable transients, it may be appropriate to limit the power disconnected in a single step to some valueΔP_{tr}^{sh} . The above limitations are summarized as follows:

$$min_k P_k \leq P_{LS} \leq \Delta P_{max}^{sh} \tag{4.6}$$

with

$$\Delta P_{max}^{sh} = \min(\sum_k P_k, \Delta P_{tr}^{sh}) \tag{4.7}$$

whereP_k denotes the individual load power behind the kth circuit breaker under control, and the minimum in eq(4.6) and the sum in eq(4.7) extend over all manoeuvrable breakers.

The control logic focuses on active power but load reactive power is obviously reduced together with active power. In the absence of more detailed information, we assume that both powers vary in the same proportion.

4.1.2 Cooperation Between Controllers

The various controllers interact in the following way:

Let us consider two close controllers:C_i monitoring bus i and C_j monitoring bus $j(j \neq i)$. Let us assume that both controllers are started by a disturbance. When C_i sheds some load, this causes the voltages to increase not only at bus i but also at neighboring buses, in particular at the monitored bus . Since $V_j$increases, the integral $\int (V^{th} - V_j(t))dt$ grows more slowly with time, thereby leading to a larger delay τ before C_j can act. For the same reason, and controller at j will shed less load once its delay is elapsed according to the methodology adopted. For larger voltage, V_j increases, may even become larger than V^{th} making C_j return to idle state. In other words, when one controller sheds load, this slows down or inhibits the controllers that compete with him to restore voltages in the same area. This cooperation avoids excessive load shedding.
Moreover, the whole system will tend to shed first where voltages drop the most. This location changes with the disturbance. Hence, the proposed scheme automatically adjusts the shedding location to the disturbance it faces. Note that the above features are achieved without resorting to a dedicated communication network. The controllers do

not exchange information, but are rather informed of their respective actions through the power system itself. This is made possible by the fact that voltages have no “inertia”: the effects of shedding are felt almost instantaneously. Neither do the controllers require a model of the system. This and the absence of communication makes the protection scheme definitely simpler and hence more reliable.

4.1.3 Tuning The Controller Parameters

The tuning of the controllers should rely on a set of scenarios combining different operating conditions and disturbances
The basic requirements are:

1. **Protection security**: The Controller does not act in a scenario with acceptable post-disturbance system response. This is normally the case following any$N-1$ contingency
2. **Protection dependability**: All unacceptable post-disturbance system responses are saved by the Controller, possibly in conjunction with other available controls
3. **Protection selectivity**: In the latter case, as few load power as possible is interrupted.

The tuning mainly consists of choosing the best values forV^{th} and . The boundsτ_{min} and ΔP^{sh}_{tr}can be chosen by engineering judgment

First, attention must be paid toV^{th}. This threshold should be set high enough to avoid excessive shedding delays, which in turn would require to shed more and/or cause low load voltages. On the other hand, it should be low enough to obey requirement 1 above. It should thus be set a little below the lowest voltage value reached during any of the acceptable post-disturbance evolutions
Next,Cshould be selected so that, for all scenarios:

- The protection sheds as few load as possible and
- some security margin is left with respect to values causing protection failure. Using the same Cvalue for all controllers makes the design definitely simpler. In the tests we performed so far, there has been no evidence that individual values would yield substantial benefits. Therefore, this simplification is adopted in the following work.

Choosing V^{th}

As already mentioned, the voltage threshold V^{th} should be set high enough in order to avoid delaying the controller actions.On the other hand, as also mentioned, V^{th} should be low enough so that no load is shed when the system post-disturbance response is acceptable. According to standard operating rules, this should be the case for any single contingency. Hence, all single outages were simulated, and the lowest voltage reached in the post-disturbance period was recorded at each bus monitored by a load shedding controller.

If it is not allowed to shed load (considering that the system response is acceptable), then V^{th} has to be decreased in order to cope with the lower voltages reached after these more severe disturbances. In this case it was found more appropriate to select non-uniform values of V^{th} ranging from 0.86 to 0.90 pu.The same value V^{th} is used for all controllers for the sake of simplicity.

In highly compensated (or capacitive) systems, the same procedure will naturally lead to higher V^{th} values, since after acceptable disturbances voltages will settle to higher values. Critical voltages will be also higher and hence V^{th} will remain close to the latter, thereby avoiding undue delays that would lead to shedding more load.

4.2 Individual Controller Design For Delayed Voltage Recovery ($dV/dt{>}0$)

An algorithm which calculates the slope of the voltage recovery trajectory was created based on successive voltage values. This slope, coupled with the most recent voltage value, can be used to establish a first-order (linear) prediction of the time at which the voltage recovery is expected to reach a certain value. (Higher order trajectory approximations were also considered but not selected so as to avoid unnecessary computational burden on the relay platform.) For the Category D contingency recovery criteria presented previously, voltages at load-serving stations where UVLS relays would be located must recover above 0.8 per-unit in 4 s or less. Any slope-based prediction of a recovery time greater than 4.0 s can therefore be used to initiate UVLS operation. This margin in recovery time directly results in minimizing the expected operation of UVLS and increases the overall security of the scheme. This margin also serves to minimize potential issues (e.g., slope calculation sensitivity) in the calculations and prediction of recovery time.

It is well known that motor loads will decelerate or even stall when subjected to longer lasting low voltages. Any action taken quickly will have a more beneficial effect and could lead to an overall reduction in the total amount of UVLS required

The first stage operating time of 1.5 s was selected based on a compromise of the need for rapid operation (when required at all) and the fact that the voltage response must be sufficiently far along in its progression toward recovery (or not) to insure an accurate slope calculation. The voltage recovery must have passed its minimum value and be on an upward trajectory. Large numbers of simulations have shown that recovery trajectories reach their lowest point roughly 1.0–1.25 s after the initial fault; initiating the first stage at 1.5 s provides adequate assurance that the recovery is on an upward trajectory.

Each stage becomes armed after the voltage remains below 80% for the specified time. However, an armed stage is not permitted to trip unless the slope calculation leads to a prediction of a recovery time (above 80%) greater than 4.0 s. Depending on the recovery trajectory, a particular UVLS relay may operate immediately after the specified time delay or at any time thereafter whenever the slope-based recovery time prediction becomes greater than 4.0 s. Full relay reset occurs at any time voltage recovers above 80%.

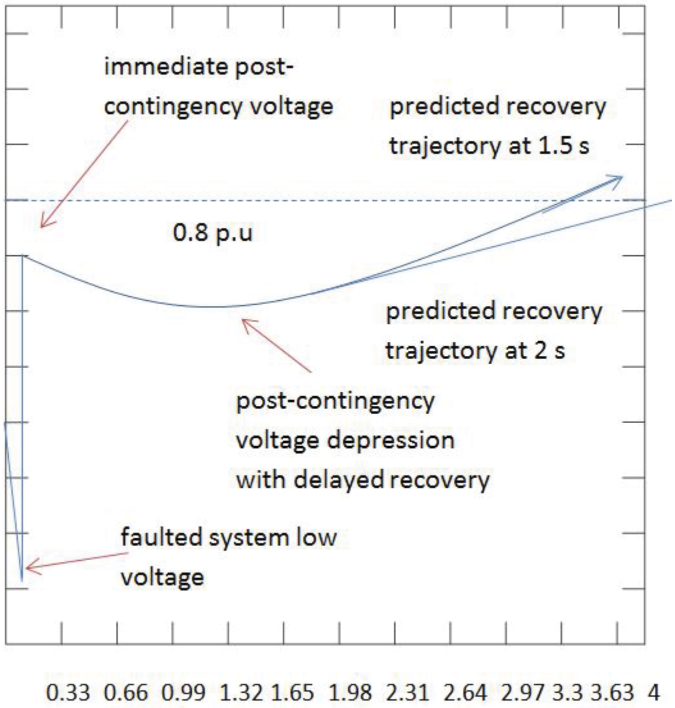

Figure 4.3: Example of voltage recovery characteristics with slope based recovery time prediction.

In Fig 4.3 is shown a simulated recovery characteristic including slope-based recovery time projections at 1.5 and 2.0 s. Assuming this recovery characteristic is seen by a Stage 1 UVLS relay, the relaywould become armed at 1.5 s. Tripping would not occur at 1.5 s because the recovery time (above 80%) projection at 1.5 s is less than 4 s. However, the relay would remain armed and tripping would occur at some point between 1.5 and 2.0 s as the slope-based recovery time (above 80%) prediction begins to exceed 4.0 s due to changes in the voltage recovery trajectory. This ability to continue to track the recovery characteristic allows the scheme to be less dependent on modelling assumptions. For example, it is possible (even likely in some cases) for motor load to stall a short time after a fault thereby worsening the entire situation. If the situation degrades, the predicted recovery could exceed 4.0 s thus activating the relay.

4.2.1 Implementation

A commercially-available programmable relay containing both voltage and current inputs was selected based on ease to program, oscillographical capability and mathematical processing power. The scheme consists of one relay per selected distribution transformer that trips multiple distribution feeders supplied by the transformer. The relay monitors both the load current through the transformer and the three phase voltages on either the high side or low side busses. Preference is given to high side voltage monitoring so as to eliminate many coordination issues with existing distribution system protection practices.

The relay is blocked from tripping load if the measured current is less than a predetermined value. Tripping lightly loaded feeders would have little or no effect on system recovery. A negative sequence inhibitor and dead bus detector was programmed to block tripping for values of negative sequence voltage greater than a preset percentage of positive sequence voltage and for voltages below a certain value. This was done to guard againstoperating during most fault conditions and potential transformer secondary fuse failures. Should the measured voltages return to a specified value for more than a predefined time period, the relay will reset the stage timer and subsequent voltage depressions will be considered new events.

Once the scheme has been armed and an under-voltage condition occurs (excluding the inhibiting criteria mentioned previously), the relay will wait for the preset stage time to pass. It continuously calculates rate of voltage recovery and compares the result to the minimum required rate of recovery. The relay can act on the result of the comparison only after this stage time has passed. The basic slope calculating principles programmed in the relay are illustrated in Fig. 4 and the equation that follow.

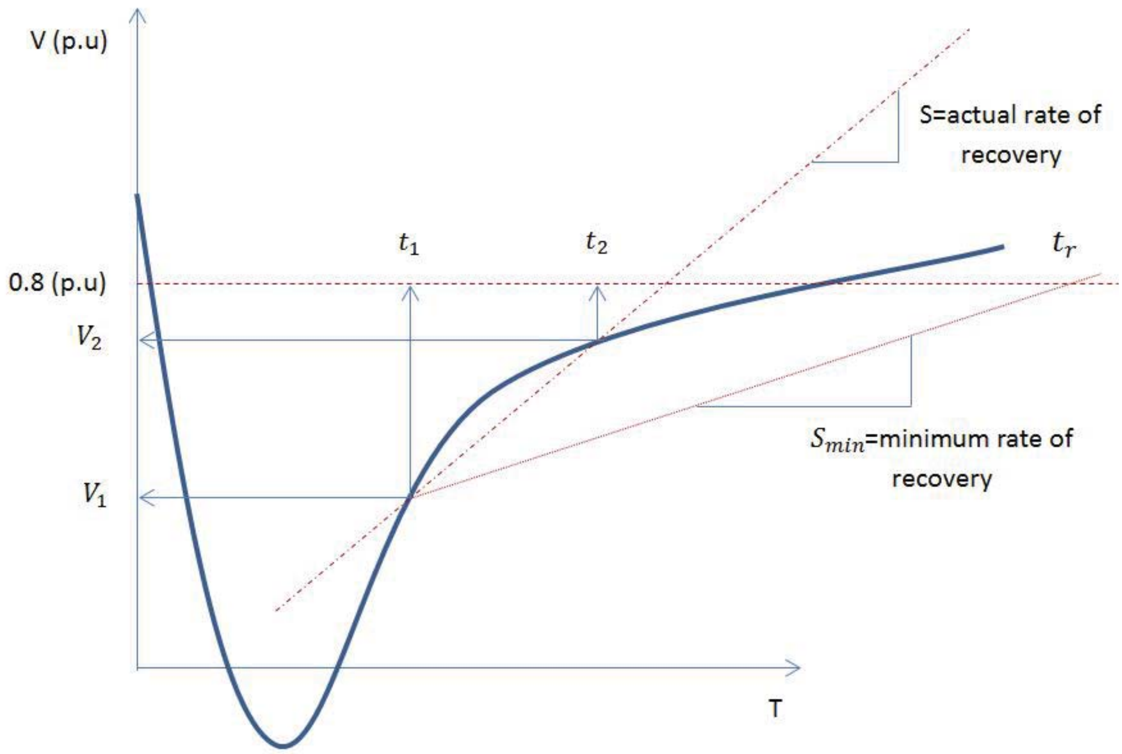

Figure 4.4: Evaluating the rate of recovery

This relay stores the previous voltage V_1 and V_2 compares it to the current voltage and then determines if

$$S = \frac{V_2 - V_1}{\Delta t} < S_{min} \tag{4.8}$$

where

S is voltage recovery slope;

S_{min} is minimum required voltage recovery slope;

V_1 is voltage rms at time t_1;

V_2 is voltage rms at time t_2;

t_1 is begin time;

$t_2$is end time ;

$\Delta t = t_2 - t_1$

The minimum required voltage recovery slope is calculated as follows:

$$S_{min} = \frac{V_R - V_1}{t_R - t_1} \tag{4.9}$$

where V_R is the predetermined voltage recovery target (0.8 pu in this scheme) and t_R is the predetermined recovery time (4.0 s in this scheme).

Once a voltage depression has lasted longer than a defined stage time, the relay captures a recording of the voltage spanning 5 s. The recording includes 2 s of pre-triggered cycled memory. This captured data will allow post mortem analysis of any future local voltage depressions. At the same time the relay will sendan alarm to the system operator. This type of alarm monitoring was dubbed "near miss or close call alarming" since alarming for every voltage depression of short duration is unwanted. If the relay should progress to actual shedding of load, a second alarm would be sent to the system operator indicating UVLS operation

Implementation In specific case

The UVLS relay operation based on design criteria pertaining to my work is elucidated here.An under-voltage condition is detected when the positive-sequence voltage falls below 0.8 pu and the relay timer is started. Following a 2.0 s time delay (to ensure the voltage is recovering), if the calculated or expected recovery time exceeds the maximum recovery time of 4.0 s from the time under-voltage event is detected, then trip is asserted.

The recovery time calculation is performed continuously in 10-cycle windows using the most recent voltage sample, V_0 and samples, V_X, where X denotes previous samples at 2, 4, 6, 8, and 10 cycle intervals. The elapsed timer times are denoted by T_0 for the current sample and T_X for the previous samples. The recovery slope and corresponding recovery times are calculated 5 times in each relay processing cycle as shown in eq(4.10) and eq(4.11).

$$Slope(n) = \frac{V_0 - V_X}{T_0 - T_X}(n = 1, 2, 3, 4, 5 \tag{4.10}$$

$$RecoveryTime, RT(n) = \frac{0.8 - V_0}{Slope(n)} \tag{4.11}$$

A 5 out of 5 voting scheme was used in the present UVLS design to determine a trip assertion, that is the calculated recovery time RT(n) should exceed the maximum recovery time of 4.0 s for all five recovery time calculations. The maximum recovery time of 4.0 s was chosen to optimize between faster operation for preventing voltage collapse and coordination with generator voltage ride-through capability curves on HV side of GSUs, which is typically around 2.0 s, following a severe voltage dip.

Since voltage collapse is a three-phase phenomenon, positive-sequence voltages were chosen as the primary operating quantity to prevent mis-operation due to unbalanced conditions. Further, a voltage window between 0.3 pu and 0.8 pu was used to determine under-voltage condition and ensure the relay is not triggered for accidental loss of potential (signal) for slow-clearing 3-phase faults which can depress bus voltages to less than 0.3 pu. Negative- and zero-sequence blocking as shown in Fig. 5b was used to enable blocking for unbalanced faults. Additional security to trip operation was added by blocking relay operation for distribution side faults

The relay will reset if at any time the measured voltage recovers above 0.82 pu (with a conditioning timer dropout delay of Td cycles, as shown in Fig. 5a) and any voltage dip following that will be considered a new event. The final trip logic is described in Fig. 5c. PLT01 represents a trip decision based on calculated slope and trip window between 2.0 s and 5.0 s provided other conditions are met. PLT04 on the other hand, does not require slope calculation and enables a trip should the positive-sequence voltage remain below 0.8 pu for more than 4.0 s following under- voltage event detection.

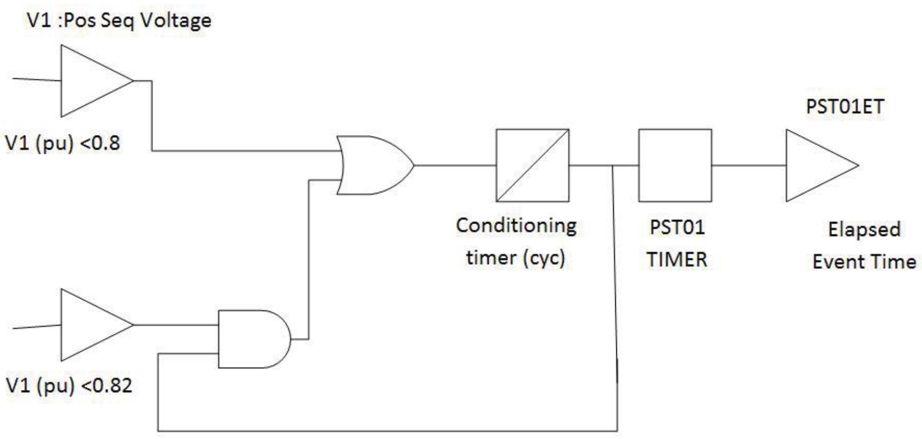

Figure 4.5: Event timer logic

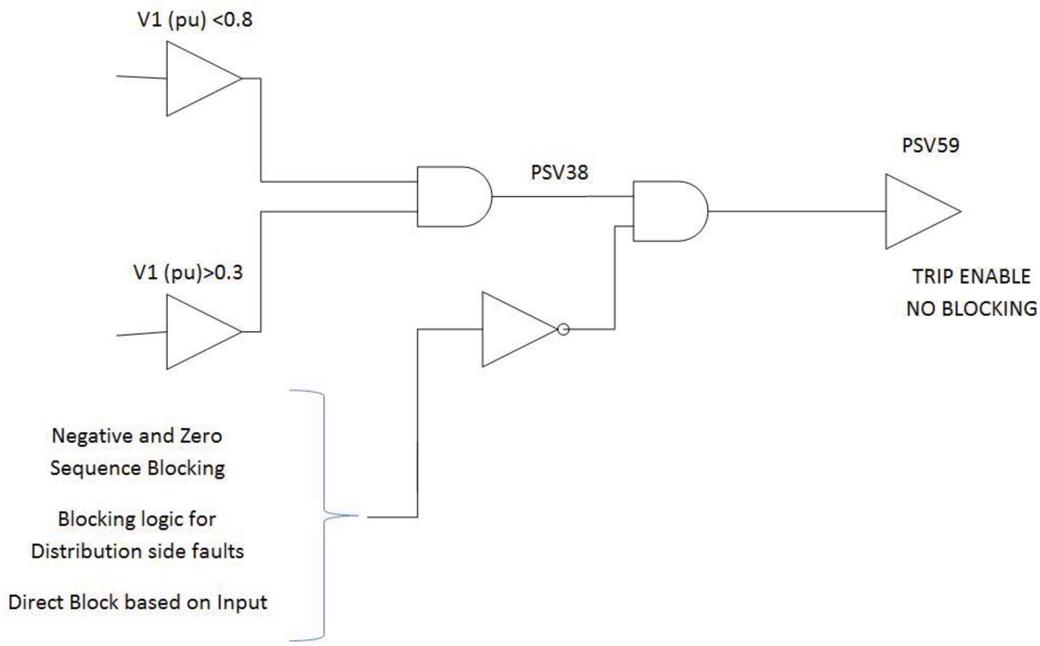

Figure 4.6: Trip supervision logic

CHAPTER 5

MODELLING OF ISLANDED MICROGRIDS

This chapter is to introduce the modelling of the radial distribution feeder system structure and study the impacts of under-voltage load shedding strategies employed to shed load .Many different distribution structures exist like networked or radial systems or based on grounding configurations. Radial distribution systems consist of a main substation with multiple feeders. They key feature about this system is it has only one source.

For radial power flow on distribution system, faults can be cleared based on the magnitude of fault current using fuses and reclosers, but if there are multiple sources on the distribution network, it is no longer radial in nature and this would require appropriate interconnection protection at the point of common coupling (PCC) between the source and the node at which it is being interconnected with possible requirement of directional or distance based relaying depending on the location of the source

5.1 Description of the System Used

The system used to employ under voltage load shedding algorithm is a modified IEEE 15 bus radial distribution system . The system has been modified to mimic behaviour of radial micro-grid and the loads are placed as shown in Fig 4.1 .the generator so placed in the system mimic the behaviour of converter interfaced distributed generators and also the switching of the distributed generators is controlled so the generation load mismatch conditions are simulated and thus initiating the working of relay. The switching of generators is also controlled to mimic delayed voltage recovery .

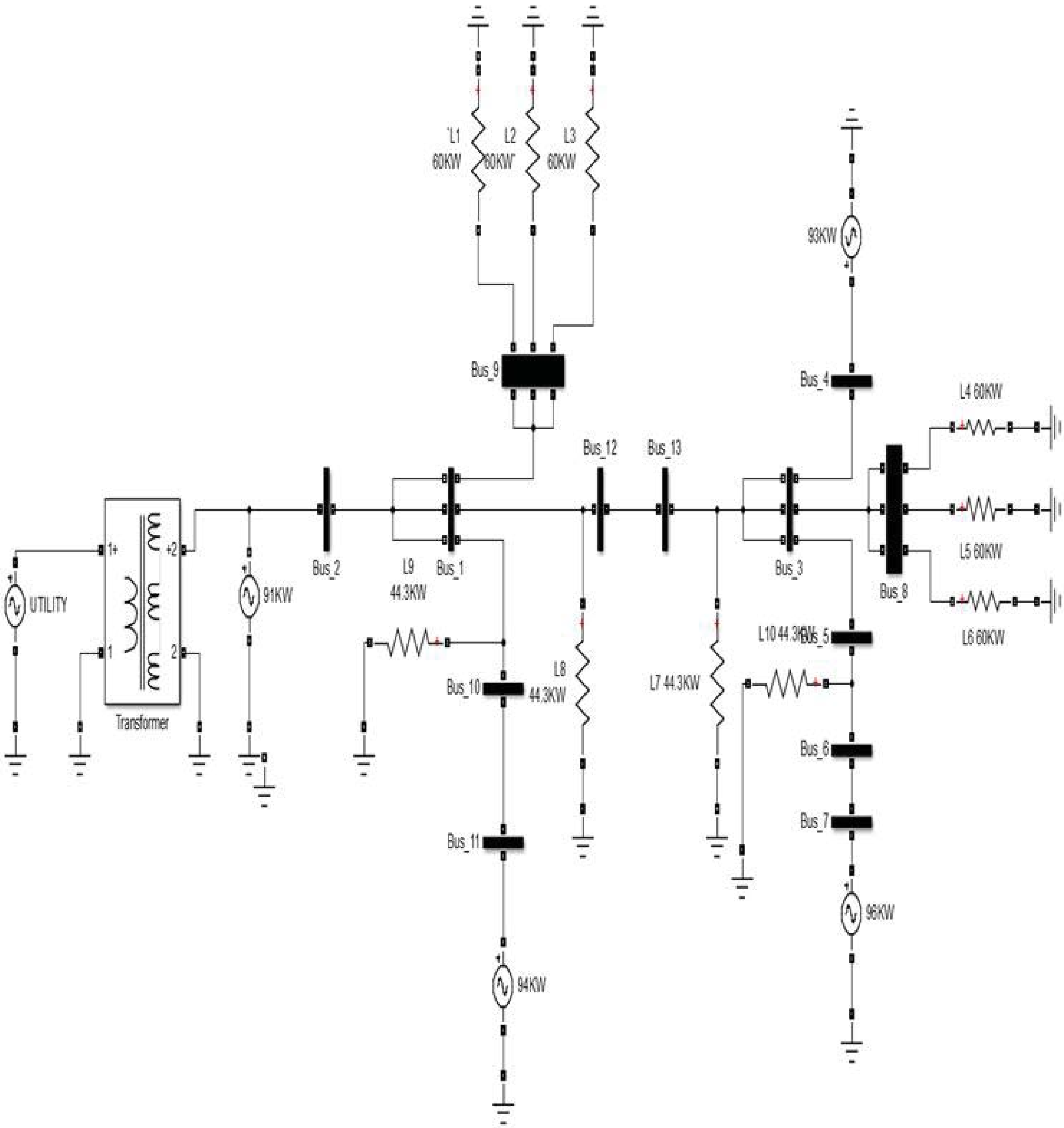

Figure 5.1: Description of the system

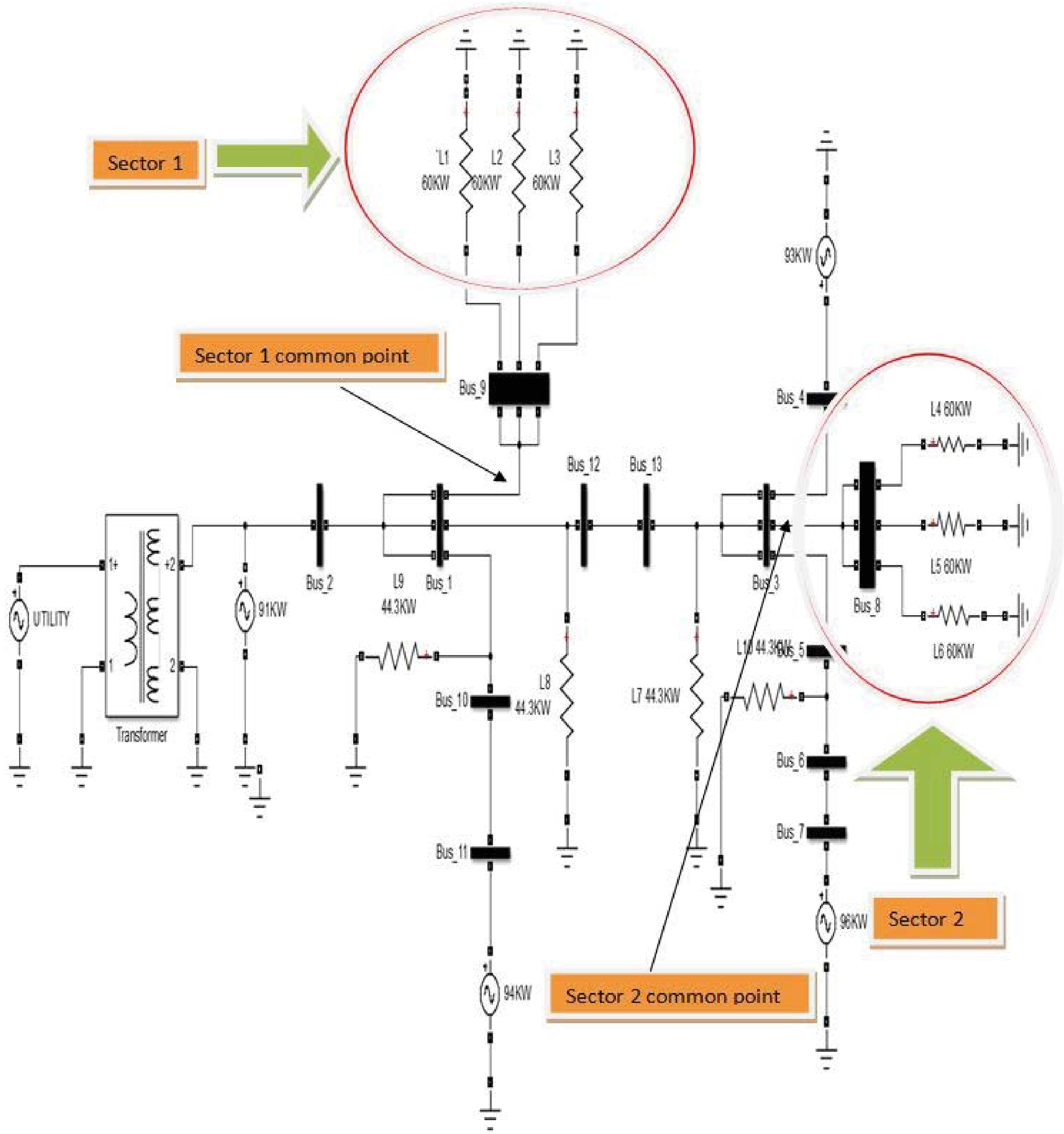

Figure 5.2: Detailed description of the system

5.2 Voltage Graphs without under-voltage relay

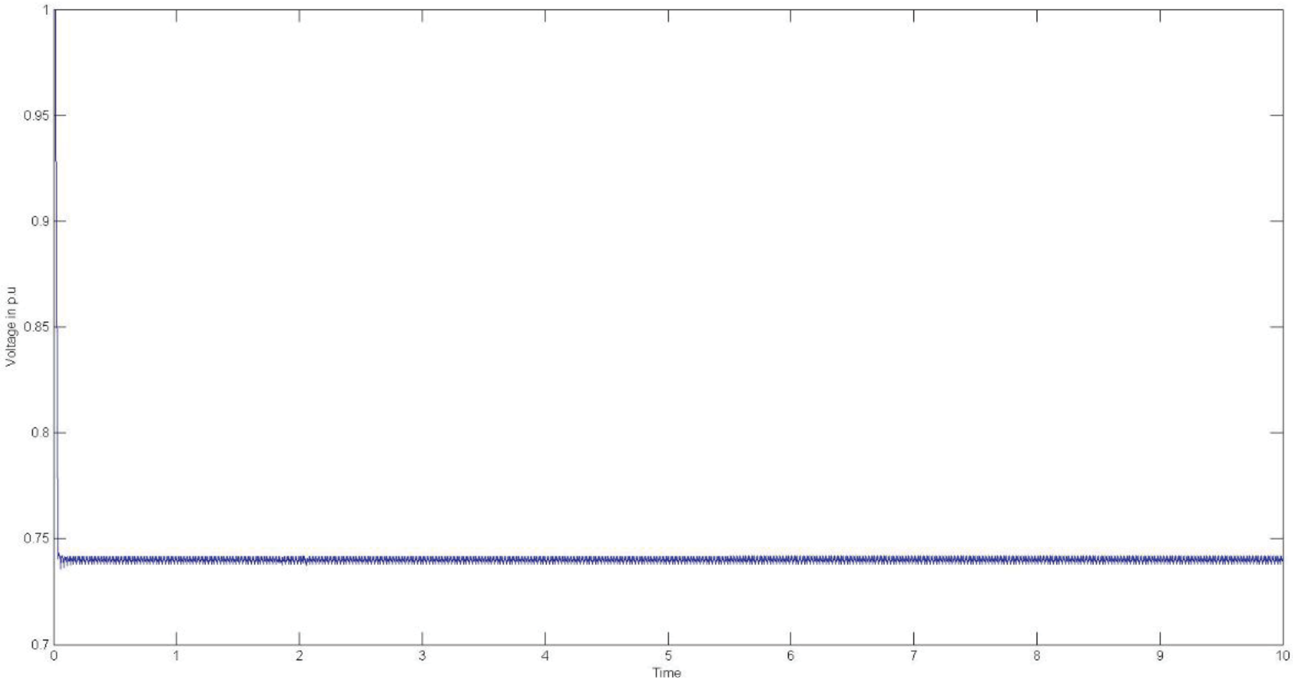

Figure 5.3: Voltage at sector 1 common point without under-voltage relay

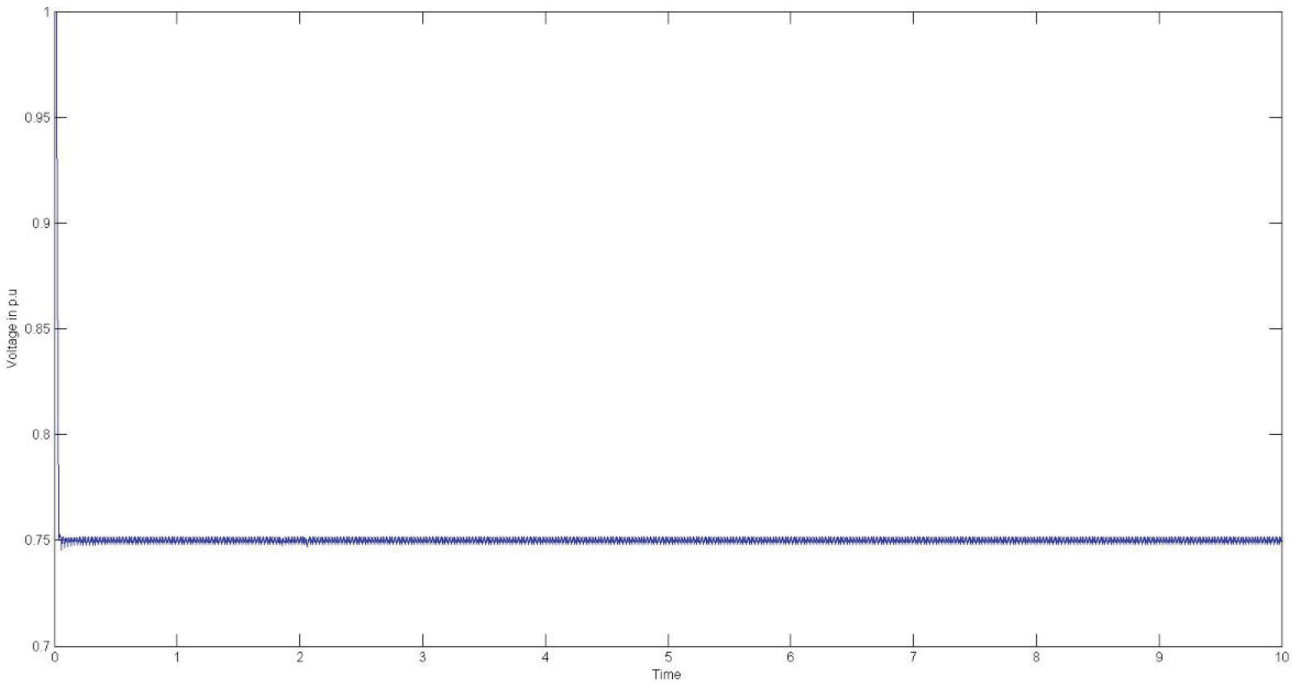

Figure 5.4: Voltage at sector 2 common point without under-voltage relay

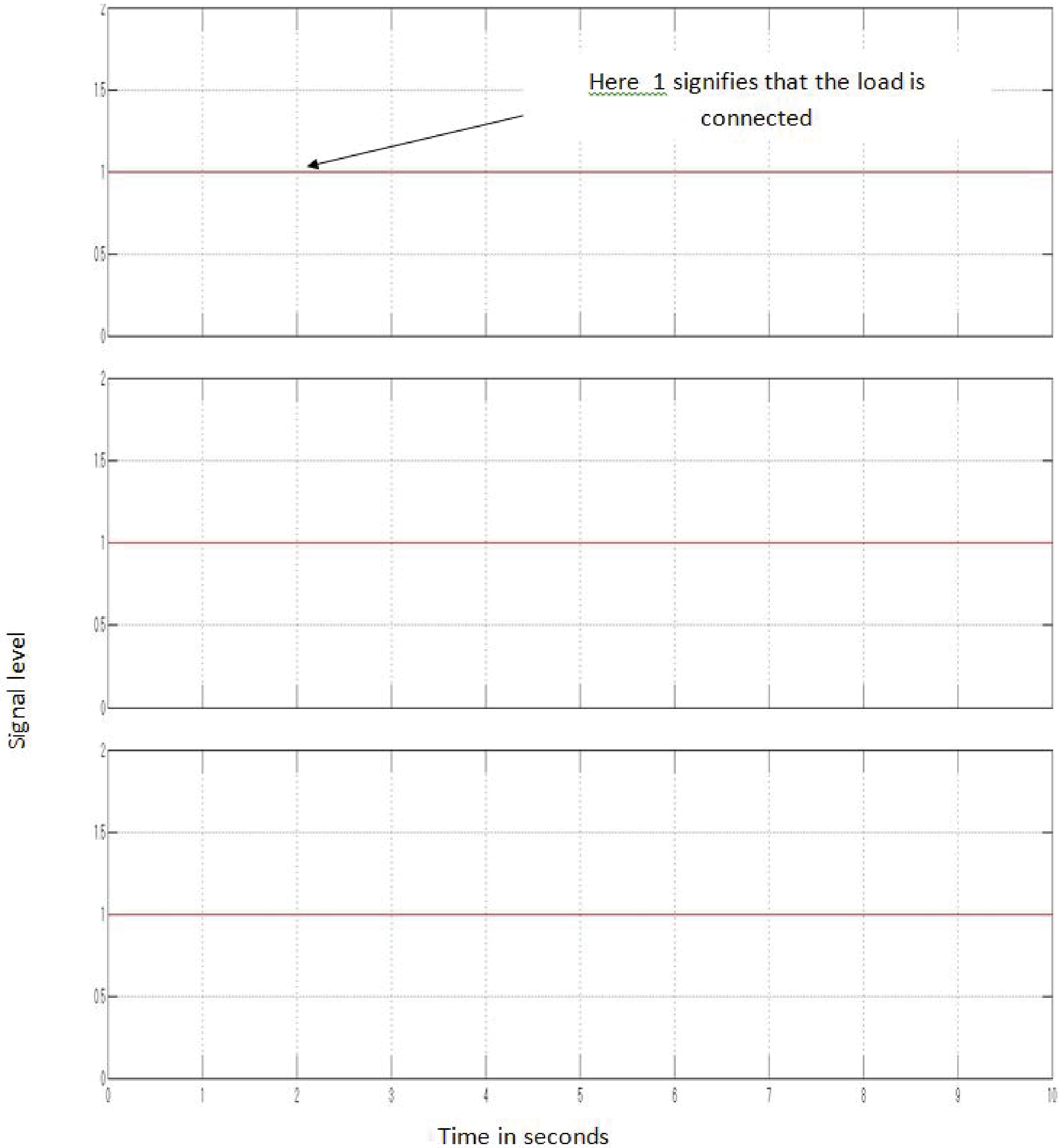

Figure 5.5: Status of loads in sector 1 and 2

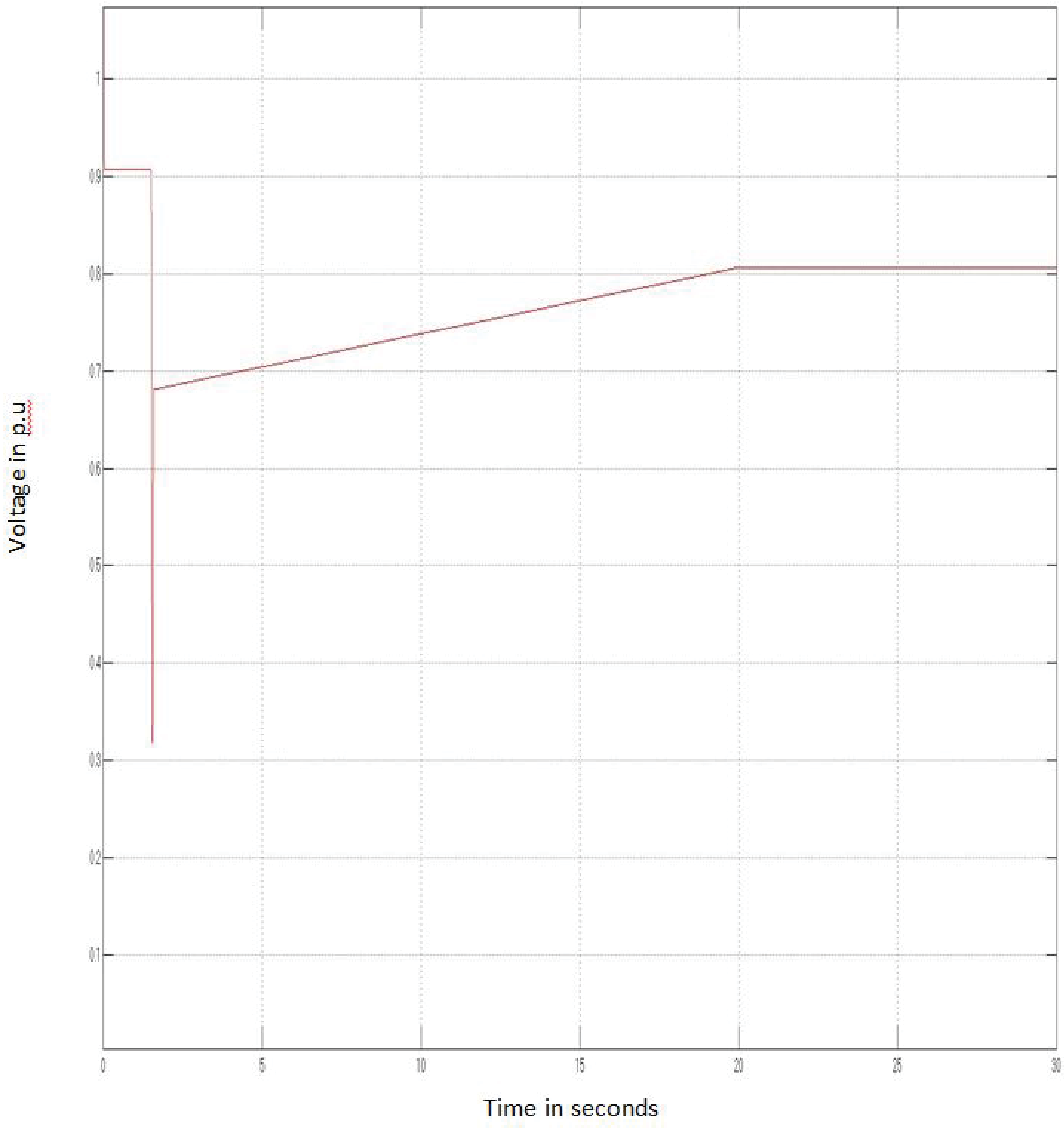

Figure 5.6: Voltage of a load showing delayed voltage recovery

CHAPTER 6

SIMULATION AND CASE STUDIES

In this chapter the effect on voltage when under voltage relay is employed is illustrated .No attempt was made to optimize the location of controllers .Instead the previously mentioned geographical zones were reused ,all of them being provided with at least one controller. We will also discuss the various unique feature of the relay developed interms of its robustness and its selectivity .

6.1 Voltage Graphs with under-voltage relay

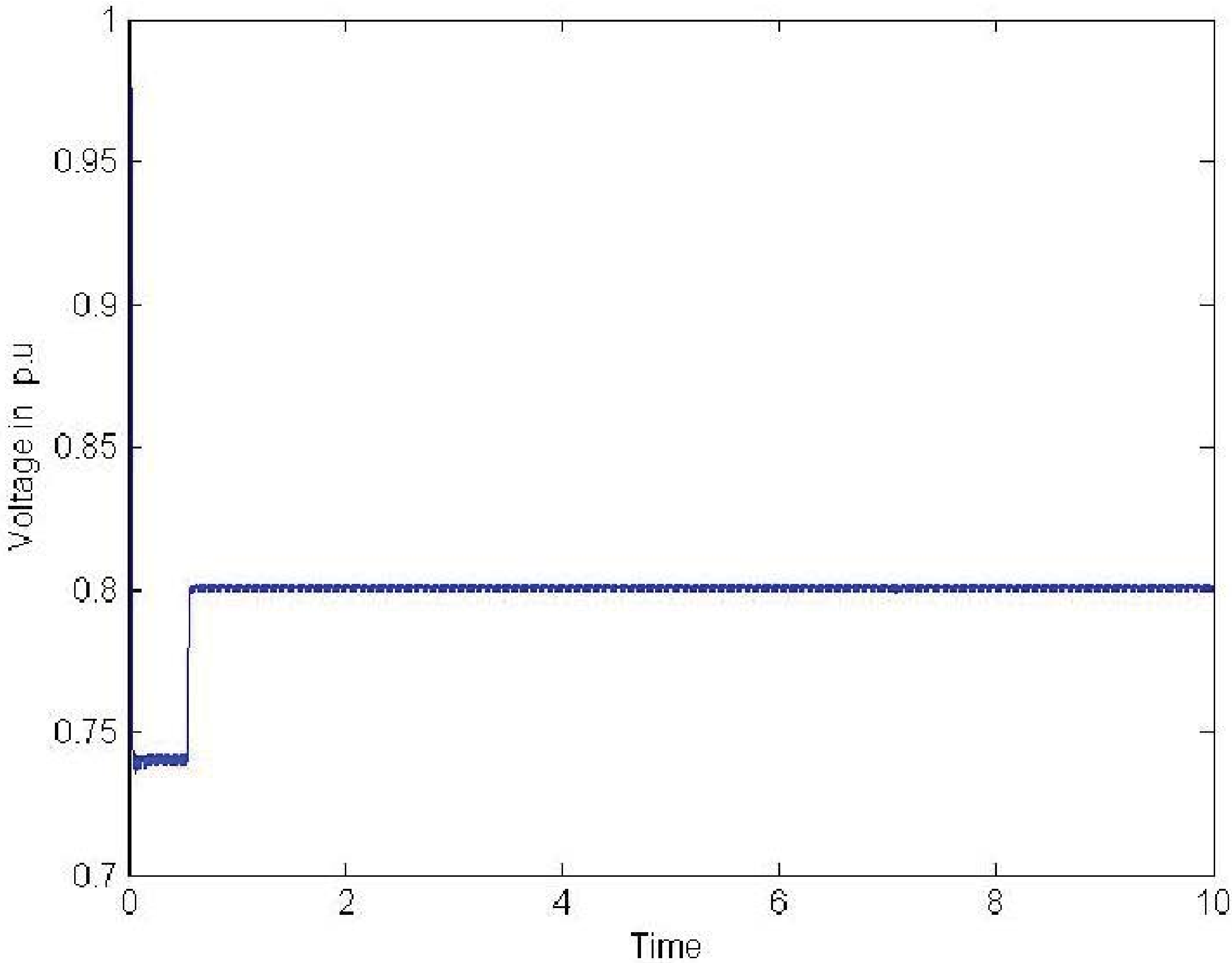

Figure 6.1: Voltage at sector 1 common point with under-voltage relay

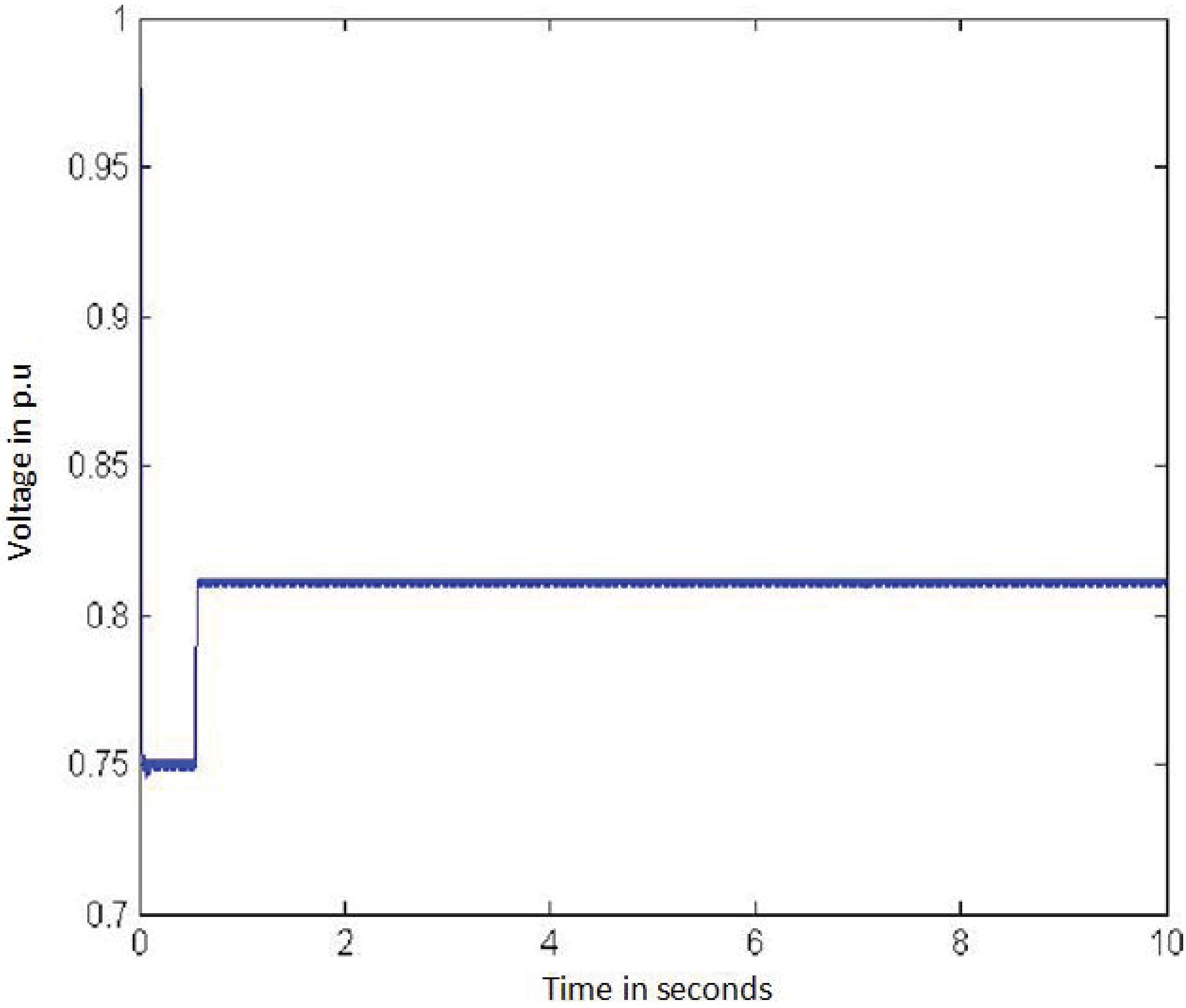

Figure 6.2: Voltage at sector 2 common point with under-voltage relay

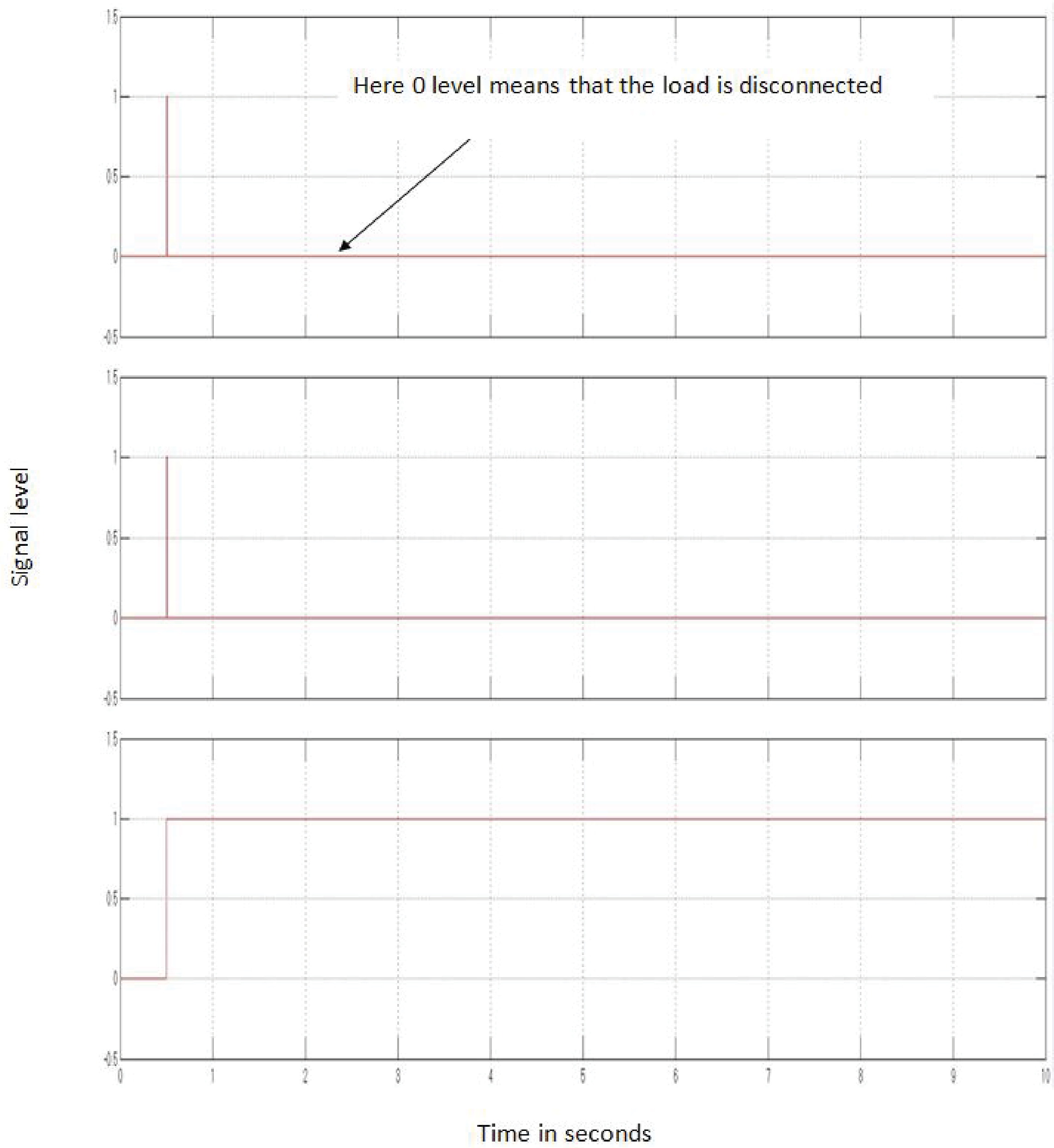

Figure 6.3: Status of loads at sector 1 with under-voltage relay

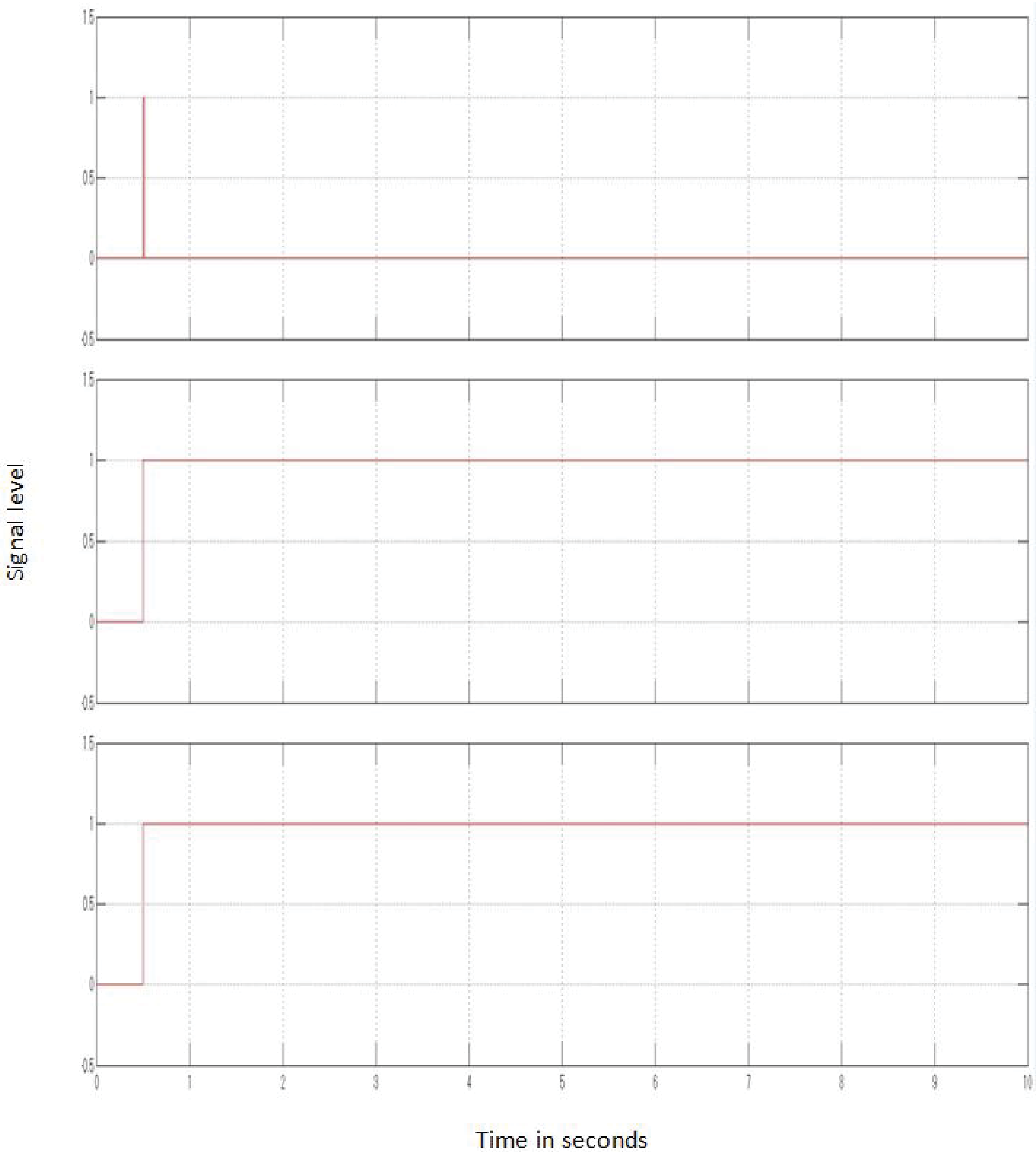

Figure 6.4: Status of loads at sector 2 with under-voltage relay

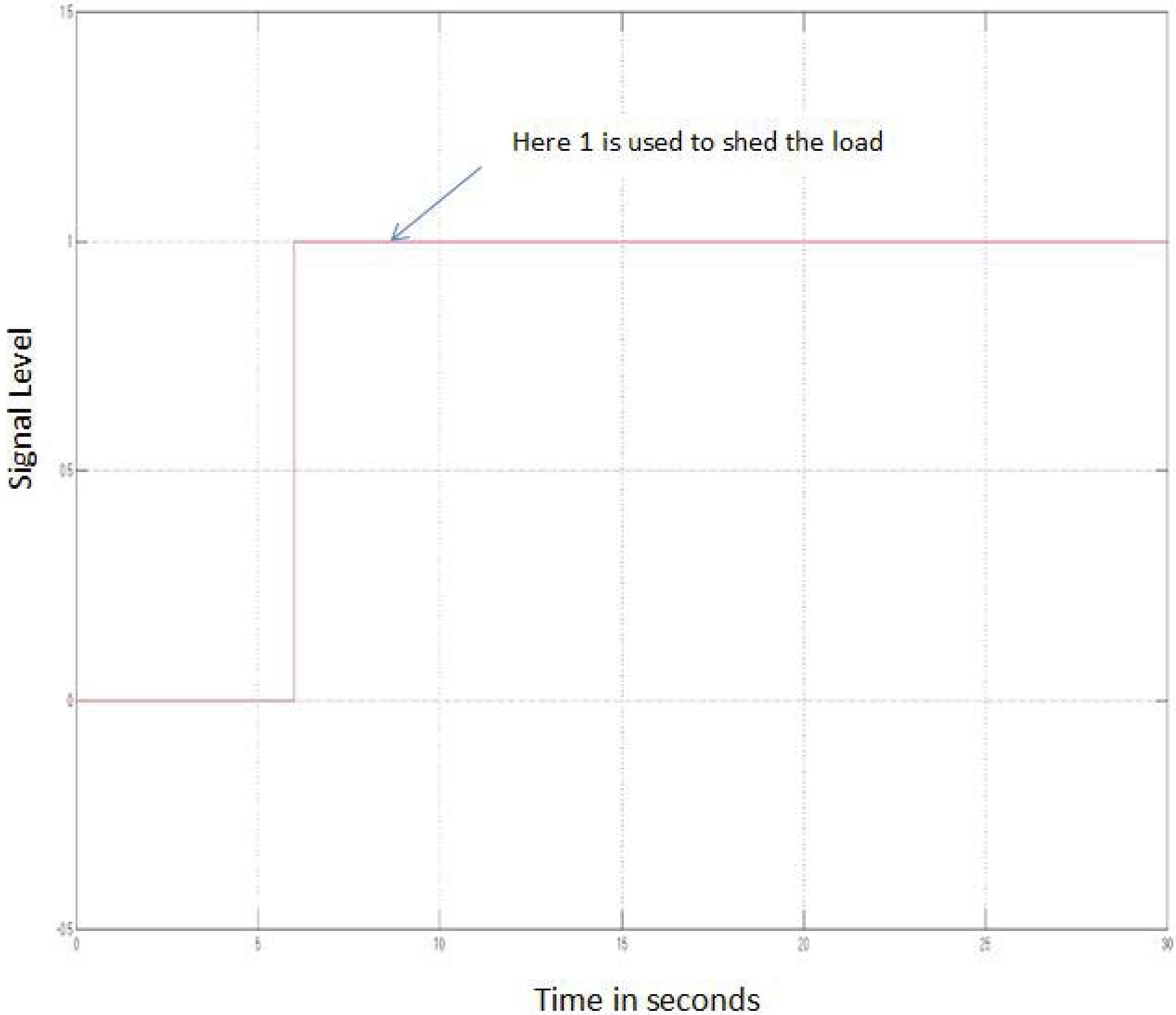

Figure 6.5: Shed signal as obtained from delayed voltage recovery relay

6.2 Results and Discussion

In this section some inferences from the results will be discussed .Detailed performance will be presented and various utilities of the algorithm will be elucidated. In addition to achieve various project goals the works foes on to explore few more cases which are a pertinent scenarios encountered in case of under-voltage.

6.2.1 Choosing the Load Shedding Controller Location

No attempt was made to optimize the location of the controllers. Instead, the previously mentioned geographical zones were re-used, all of them being provided with at least one controller. By so doing, a total of 2 controllers were considered, which are denoted $C_i(i = 1, 2)$ in the sequel .in sectors 1 and 2 as shown in fig 4.2. As individual loads at distribution level were not known from the available data, power was shed homothetically in each cluster, with a lower limit of 60 MW.

6.2.2 Detailed example of performance

In this section we will illustrate how the controllers interact with each other.

Let us consider a disturbance to the left of sector 1 as shown in 6.6.In the absence of load shedding the unstable voltage evolution observed by controller C_1 as shown in 5.3 and due to the action of C_1 the voltage improve as shown in 6.2.and this controller sheds 120 MW of load as shown in 6.4 .Since the voltage as seen by $C_2$is also below 0.8pu but the dip is not to severe but since the voltage is below 0.8pu it acts and sheds 60MW of load which is the least amount of load which can be shed in a single instant .This is shown in 6.5.So this clearly shows the adaptive feature of controller and also there is a minute difference in the instants at which the controllers acts and this is due the common value of C which is used across the controllers i.e. $\tau_1 > \tau_2$.

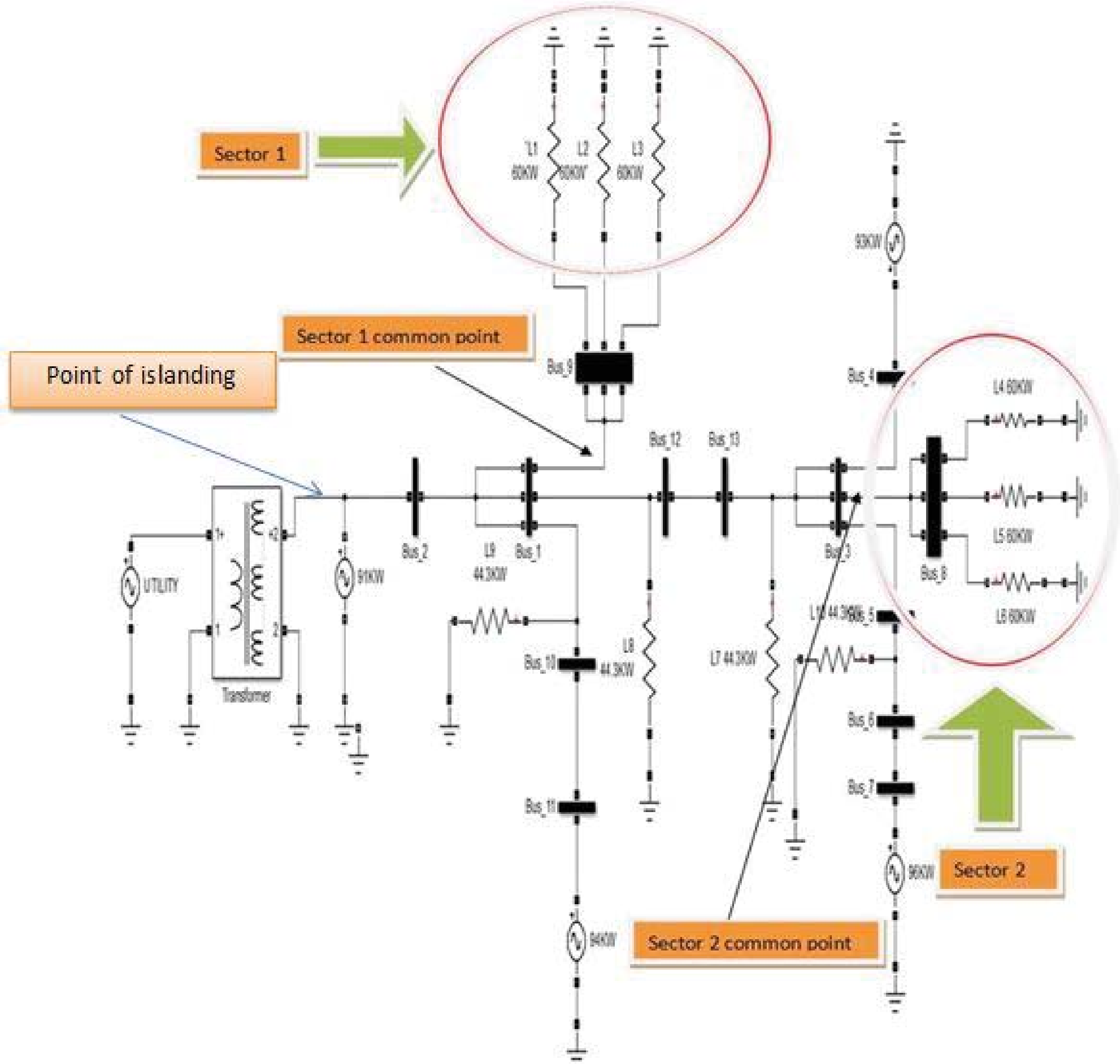

Figure 6.6: Disturbance area location

6.2.3 Relay selectivity in terms of location

This section illustrates one aspect of SPS selectivity, i.e., the ability of the distributed protection to adjust the shedding location to the disturbance it faces. This relates to the fact that the area experiencing the largest voltage drops changes with the disturbance, and different controllers are activated.

The data of each controller is as shown in the table

Disturbance	Sector	Controller	Shedding steps (MW)
D_1	1	1	60+60
D_1	2	2	60

As can be seen the action of controllers is largely affected by the location of disturbance

6.2.4 Relay selectivity in terms total power cut

Another aspect of selectivity is the ability to adjust the load shedding amount to the severity of the disturbance.

Let us stress that the proposed distributed controller structure is not claimed to yield minimum load shedding, although the controllers' settings have been chosen so as to meet this objective. Since to minimize the amount of total load to be shed requires a communication infrastructure between the buses therefore no claims about optimality of amount of load shed is made.

6.2.5 Relay robustness with respect to load model uncertainty

As already mentioned, the closed-loop nature of each controller compensates for uncertainties in dynamic system behaviour. This section aims at illustrating the robustness of the proposed scheme with respect to load modelling inaccuracies .Here since the exponential model is used and the voltage dependence factor is determined before hand and that parameter varies between 1 and 2 so for any value the controller works equally well.

6.2.6 Relay robustness with respect to component failure

Another aspect of robustness has to do with the possible failure of some controllers. This section aims at demonstrating the performance of the proposed scheme in this respect.

Since the controllers operate on the base of voltage fluctuations at the local point and the severity of voltage drop so a minor malfunction doesn't have a much affect on the independent function of these controllers .

6.2.7 Characteristics of relay for delayed voltage recovery

The relay operation logic is used to discriminate between conditions that require load shedding and conditions that do not. The relay event timer operation logic, along with trip supervision logic and final trip expression is shown in 4.5 ,4.6 and6.7

Since voltage collapse is a three-phase phenomenon, positive-sequence voltages were chosen as the primary operating quantity to prevent disoperation due to unbalanced conditions. Further, a voltage window between 0.3 pu and 0.8 pu was used to determine under-voltage condition and ensure the relay is not triggered for accidental loss of potential (signal) for slow-clearing 3-phase faults which can depress bus voltages to less than 0.3 pu. Negative- and zero-sequence blocking as shown in 4.6 was used to enable blocking for unbalanced faults. Additional security to trip operation was added by blocking relay operation for distribution side faults.

The relay will reset if at any time the measured voltage recovers above 0.82 pu (with a conditioning timer dropout delay of Td cycles, as shown in 4.5) and any voltage dip following that will be considered a new event. The final trip logic is described in 6.7. PLT01 represents a trip decision based on calculated slope and trip window between 2.0 s and 5.0 s provided other conditions are met. PLT04 on the other hand, does not require slope calculation and enables a trip should the positive-sequence voltage remain below 0.8 pu for more than 4.0 s following under-voltage event detection

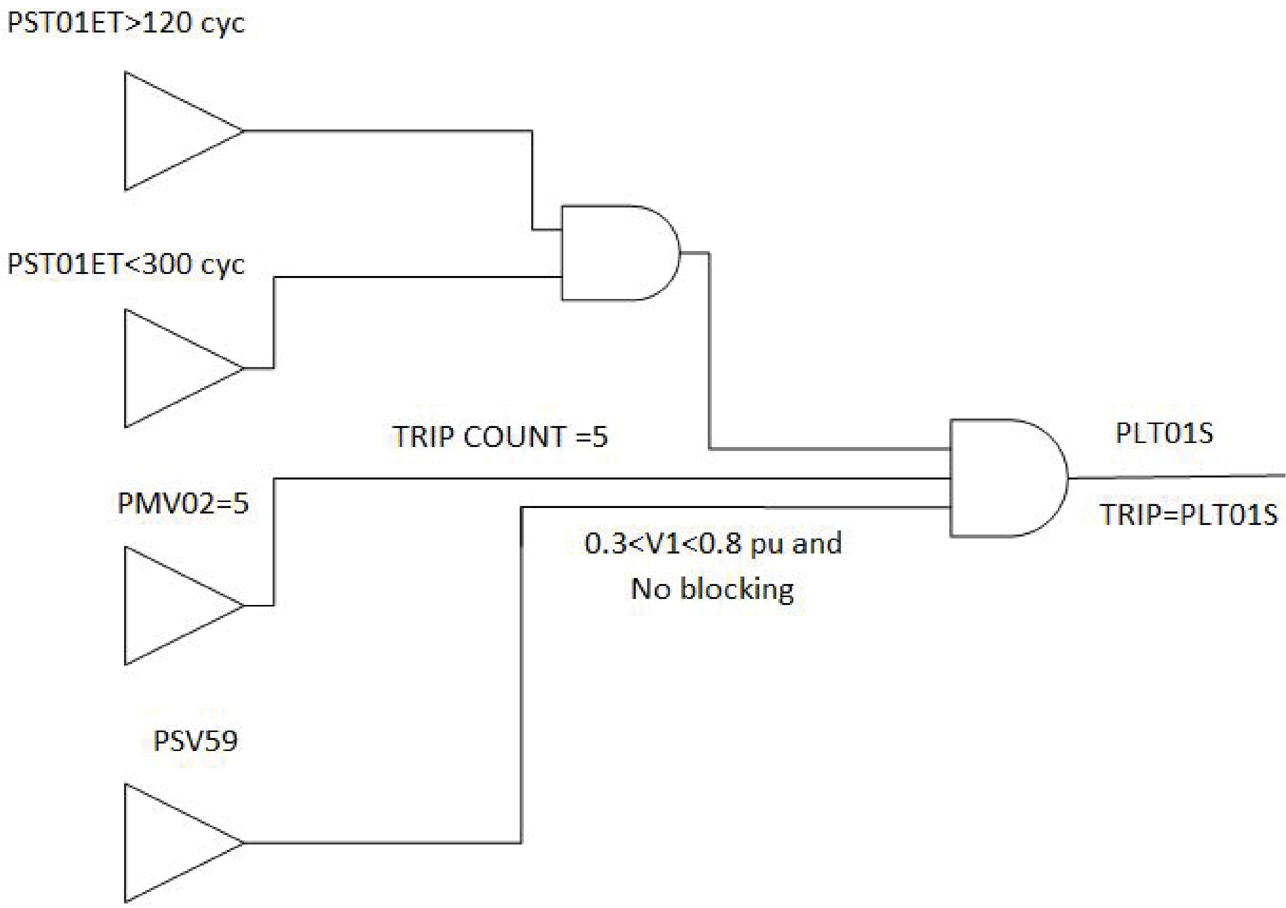

Figure 6.7: Latch targets and final trip expression

The relay operates in scenarios where the loads non restart able motor loads like small ac motor loads .In such scenarios the loads needs to be shut down and using the logic stated above the load is shed as shown in 6.6

CHAPTER 7

CONCLUSION

In this work, a novel method for active load control in islanded micro-grids is presented. This demand dispatch strategy is based on the micro-grid voltage as a trigger, which is enabled by the chosen active power control strategy for the generators. The active power is balanced V_g/V_{dc} by the droop control strategy that delays power changes. In case the adjustment voltage is exceeded, it is combined P_{dc}/V_g with droop control, which changes the output power of the DG unit to avoid violation of the voltage limits. The adjustment voltage can be chosen depending on the power control abilities of the generators. A proper choice of the adjustment voltage allows to fully exploit the renewable power sources and even to increase their degree in the micro-grid.

It is shown that with the application of these droop controllers for the generators and because of the - linkage in weak low-voltage electrical networks, the rms voltage is a good measure for the power production versus consumption in the micro-grid. Therefore, the loads can adjust their temporarily power consumption according to the voltage level to enable demand dispatch. This work renders a proof of concept for the micro-grid voltage as a trigger for a novel demand dispatch strategy in islanded micro-grids. The control of the active loads gives the same effects and has the same trigger as the control of the generators. Therefore, it is possible to increase the part in the micro-grid that is contributing to the power balancing, which gives more security for a stable operation. Furthermore, there is no need for a communication link neither for the primary active and reactive power control of the generators nor for the active load control. It is shown that the presented demand dispatch strategy improves the reliability of islanded micro-grid and leads to reduction of the line losses. With the combination of the active power control and the presented active load control, the renewable energy can be exploited optimally, allowing higher amounts of renewable DG units in islanded micro grids

A new under-voltage load shedding scheme has been proposed and realistic tests have been reported demonstrating:

- Its response-based and closed-loop operation allowing adjusting to the severity of the situation
- Its distributed structure allowing adjusting to the disturbance location
- Its robustness with respect to unexpected load behaviours or controller failures
- Its simplicity, since there is no dedicated communication between controllers and no system model is needed

Of course, the work only tackled the control logic. Validation with full time simulation, design measurement filtering schemes, number of controllers, clustering of loads, etc. is important aspects to be considered before implementing such a system protection scheme. Variants of the proposed scheme may be also thought of, for use in a centralized protection allowing the controllers to exchange information.

In this work we have also considered under-voltage load shedding algorithm based on slope of voltage recovery calculations .In particular This scheme uses a slope-based recovery criteria of 4.0 s following under-voltage event detection, with a 2.0 s initial delay window included to ensure the voltages are recovering. Detailed trip supervision logic was incorporated to improve security of relay operation. In our case the relay is used to logically arrive at shed signal rather than doing any calculation in particular.

REFERENCES

1. **Balaguer, I. J.**, **Q. Lei**, **S. Yang**, **U. Supatti**, and **F. Z. Peng** (2011). Control for grid-connected and intentional islanding operations of distributed power generation. *IEEE Transactions on Industrial Electronics*, **58**(1), 147–157. ISSN 0278-0046.

2. **Balanathan, R.**, **N. C. Pahalawaththa**, **U. D. Annakkage**, and **P. W. Sharp** (1998). Undervoltage load shedding to avoid voltage instability. *IEE Proceedings - Generation, Transmission and Distribution*, **145**(2), 175–181. ISSN 1350-2360.

3. **Ceja-Gomez, F.**, **S. S. Qadri**, and **F. D. Galiana** (2012). Under-frequency load shedding via integer programming. *IEEE Transactions on Power Systems*, **27**(3), 1387–1394. ISSN 0885-8950.

4. **Hajimohamadi, N.** and **H. Bevrani**, On load shedding in microgrids. *In 18th Electric Power Distribution Conference*. 2013.

5. **Katiraei, F.** and **M. R. Iravani** (2006). Power management strategies for a microgrid with multiple distributed generation units. *IEEE Transactions on Power Systems*, **21**(4), 1821–1831. ISSN 0885-8950.

6. **Katiraei, F.**, **M. R. Iravani**, and **P. W. Lehn** (2005). Micro-grid autonomous operation during and subsequent to islanding process. *IEEE Transactions on Power Delivery*, **20**(1), 248–257. ISSN 0885-8977.

7. **Kolluri, S. V.**, **J. R. Ramamurthy**, **S. M. Wong**, **M. Peterson**, **P. Yu**, and **M. R. Chander**, Relay-based undervoltage load shedding scheme for entergy's western region. *In 2015 IEEE Power Energy Society General Meeting*. 2015. ISSN 1932-5517.

8. **Laaksonen, H.**, **P. Saari**, and **R. Komulainen**, Voltage and frequency control of inverter based weak lv network microgrid. *In 2005 International Conference on Future Power Systems*. 2005.

9. **Lei, Q.**, **F. Z. Peng**, and **I. J. Balaguer**, Islanding control of dg in microgrids. *In 2009 IEEE 6th International Power Electronics and Motion Control Conference*. 2009.

10. **Lopes, J. A. P.**, **C. L. Moreira**, and **A. G. Madureira** (2006). Defining control strategies for microgrids islanded operation. *IEEE Transactions on Power Systems*, **21**(2), 916–924. ISSN 0885-8950.

11. **Malekpour, A. R.**, **A. R. Seifi**, **M. R. Hesamzadeh**, and **N. Hosseinzadeh**, An optimal load shedding approach for distribution networks with dgs considering capacity deficiency modelling of bulked power supply. *In 2008 Australasian Universities Power Engineering Conference*. 2008.

12. **Otomega, B.** and **T. V. Cutsem** (2007). Undervoltage load shedding using distributed controllers. *IEEE Transactions on Power Systems*, **22**(4), 1898–1907. ISSN 0885-8950.

13. **Vandoorn, T. L.**, **B. Renders**, **L. Degroote**, **B. Meersman**, and **L. Vandevelde**, Power balancing in islanded microgrids by using a dc-bus voltage reference. *In SPEEDAM 2010*. 2010*a*.

14. **Vandoorn, T. L.**, **B. Renders**, **L. Degroote**, **B. Meersman**, and **L. Vandevelde** (2011). Active load control in islanded microgrids based on the grid voltage. *IEEE Transactions on Smart Grid*, **2**(1), 139–151. ISSN 1949-3053.

15. **Vandoorn, T. L.**, **B. Renders**, **B. Meersman**, **L. Degroote**, and **L. Vandevelde**, Reactive power sharing in an islanded microgrid. *In 45th International Universities Power Engineering Conference UPEC2010*. 2010*b*.

16. **Ye, L.**, **Z. Baohui**, **B. Zhiqian**, and **L. Junzhe**, An adaptive load shedding method based on the underfrequency and undervoltage combined relay. *In 2015 34th Chinese Control Conference (CCC)*. 2015.

17. **Yu, K.**, **Q. Ai**, **S. Wang**, **J. Ni**, and **T. Lv** (2016). Analysis and optimization of droop controller for microgrid system based on small-signal dynamic model. *IEEE Transactions on Smart Grid*, **7**(2), 695–705. ISSN 1949-3053.

18. **Zhang, H.**, **C. S. Lai**, and **L. L. Lai**, A novel load shedding strategy for distribution systems with distributed generations. *In IEEE PES Innovative Smart Grid Technologies, Europe*. 2014. ISSN 2165-4816.